Assessment of groundwater vulnerability to pollution on the territory of the Upper Kama salt deposit

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CHAPTER 1

INTRODUCTION

Actuality. The Berezniki-Solikamsk industrial hub area in Perm Krai (Russia) is characterized by extensive development of the chemical industry, generally associated with development of the Upper Kama potassium and magnesium salts deposit. Development of the deposit is performed by underground mining, depth of mine channel changes from 100 to 500 m. At the present time underground mining operations are conducted at six potash mines. On the base of the deposit there is extracted sylvinite (raw material for production of potash fertilizers), carnallite (receiving artificial carnallite for magnesium industry), halite and brine (raw material for soda production) (Kudryashov et al., 2004). The content of sylvite in the ore of the deposit varies from 25% to 32%. The remainder part is halite (60 – 75%) and insoluble residue (clay and carbonate particles) whose content in different parts of the field ranges from 1.5 to 6.5% (9%). After enrichment, the halite and clay as waste products are taken place above the ground surface in form of dumps composed of halite waste (80-93 %) and clay-salt sludge (7-10 %). They both are the main sources of salinization of ground and surface waters, soils and rocks in the zone of active water exchange. By itself, salt is not dangerous for a human body. However, increasing the concentration of salts in water more than 1 g/L makes it useless for drinking and, in some cases, for domestic needs. Increasing of the salt concentration in the groundwater over a certain level has the negative impact on root system of plants and fauna of water reservoirs in the areas of the salt water discharge. Besides of that, on the territory there are some oil deposits, lying under the salt deposit. Their development has also negative impact to groundwater.

In the investigated territory, with a land area of about 2500 km^2, are located two large towns Berezniki and Solikamsk with a total population of about 250 thousand people and a number of smaller settlements. On its territory there are 20 large groundwater intake structures. In this regard, the assessment of groundwater vulnerability in this region is an actual problem.

To protect groundwater and surface water from salinization there is provided construction of hydroengineering structures of salt dumps and sludge storages, which are designed by JSC “Hallurgy” (city of Perm). The performed vulnerability assessments can be taken into account in future when selecting placement of waste of the salt industry.

The purpose of the work: 1) to perform the groundwater vulnerability assessment to pollution on the territory of the Upper Kama potassium salt deposit using the method SINTACS and a method based on calculation of travel time of a contaminant (chloride ion) to an aquifer.

2) to make the comparative analysis of these methods, to reveal their advantages and disadvantages for regional assessments.

In accordance with this purpose there were assigned the following **tasks**:

1. To perform the analysis of the existing methods of groundwater vulnerability assessment to pollution;

2. To study features of groundwater runoff formation of the Upper Kama potassium salt deposit;

3. To study natural conditions of the observable territory and their effect on groundwater vulnerability.

4. To evaluate the effect of the unsaturated zone represented by two layers of the Quaternary and the Permian deposits on the time of travel of chloride ion (Cl^-) to the groundwater level.

5. To evaluate the vulnerability of the groundwater of the Sheshminsky water-bearing complex and the Solikamsk terrigenous-carbonate complex to chloride ion pollution.

To perform the set purpose there were carried out analysis and systematization of archival and published works, gathering, digitization and geocoding available materials and data characterizing conditions and factors of groundwater formation and groundwater vulnerability, creation of appropriate geodatabases and thematic maps in formats suitable for visualization and processing by methods of GIS technology (Spatial Analyst).

The scientific novelty of the work consists in the following:

- Two maps of groundwater vulnerability for the territory of the Upper Kama potassium salt deposit were made by method SINTACS and by method based on calculation of time of travel of a contaminant to groundwater.
- There was made the comparative analysis of these methods.
- There was estimated the role of infiltration as a factor defining velocity and the time of travel of a contaminant through the unsaturated zone.
- There were revealed the particularities of intrinsic groundwater vulnerability depending on environment characteristics of the observable territory.

The conducted researches allow qualitatively and quantitatively assess groundwater vulnerability of the territory of the Upper Kama potassium salt deposit. The results of the executed researches can be used for:

- assessment of vulnerability and forecast of probability of chlorides inflow into groundwater on the perspective sites of the deposit;

- rational choice of safest places for location of water intake structures;
- substantiations of a database for the future researches;
- hydrogeological substantiation of various water protection measures.

PhD Thesis Structure. The thesis contains 134 pages, consists of five chapters and includes 40 tables, 56 figures and list of references consisting of 87 items.

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CHAPTER 2

MODERN METHODS OF GROUNDWATER VULNERABILITY ASSESSMENT TO CONTAMINATION

2.1. General provisions; basic concepts and definitions of groundwater vulnerability assessment

The concept of groundwater vulnerability is derived from the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts, especially with regard to pollutants entering the subsurface environment. The term "*vulnerability of groundwater to contamination*" was probably first introduced in France in the late 1960s (Albinet, M., Margat, J., 1970). The general intention was to show that the protection provided by the natural environment varied from place to place. Thus the fundamental principle of groundwater vulnerability is that some land areas are more vulnerable to pollution than others.

Results of vulnerability assessment are portrayed on a map showing various homogeneous areas, sometimes called cells or polygons, which have different levels of vulnerability. The differentiation between the cells is, however, arbitrary because vulnerability maps only show relative vulnerability of certain areas to others, and do not represent absolute values (Zektser I.S., Everett L.G., 2004).

Although the general concept has been in use for more than thirty years, there is not really a generally accepted definition of the term.

The Committee on Techniques for Assessing Groundwater Vulnerability of the U.S. National Research Council (1993) defined *groundwater vulnerability to contamination* as 'the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above the uppermost aquifer'. However later in the text, the Committee also differentiated two general types of vulnerability: specific vulnerability (referenced to a specific contaminant, contaminant class, or human activity) and intrinsic vulnerability, which does not consider the attributes and behaviour of specific contaminants.

The U.S. General Accounting Office (1991) used the term '*hydrogeological vulnerability*' for the instrinsic susceptibility of an aquifer to contamination and the term 'total vulnerability' for vulnerability that is a function of hydrogeological factors, as well as of the land-use practices and contaminant loading.

Civita (1987) the *intrinsic aquifer vulnerability to contamination* is the specific susceptibility of aquifer systems, in their parts, geometry and hydrodynamic settings, to receive and diffuse fluid and/or hydro-vectored contaminants, the impact of which, on the groundwater quality, is a function of space and time.

Chilton (2006) defined *vulnerability* as the intrinsic properties of the strata separating a saturated aquifer from the land surface which determine the sensitivity of that aquifer to being adversely affected by pollution loads applied at the land surface.

With the course of time, the concept of vulnerability varied, but the most widely accepted definition proposed by scientists Vrba (1994): *groundwater vulnerability* is a natural intrinsic property of the groundwater system that depends on the ability or sensitivity of this system to cope with natural processes and human impacts.

Among the most famous scientists involved in the groundwater vulnerability research should be noted the work of J.Margat, L.Aller, M. Civita, S.S.D.Foster, J.Vrba, A.Zaporozec, A. Aureli, M. J.Chilton and many other.

The opposite notion is **groundwater protection** from pollution. The extent of groundwater protection from pollution is the property of a natural system that it makes possible to preserve for a predicted period, and the composition and quality of groundwater in keeping with the requirements for its practical use. The larger the extent of groundwater protection, the smaller groundwater's vulnerability to pollution (Zektser I.S., Everett L.G, 2000).

Term "*protection of groundwater*" is more commonly used in Russia, where studies of protection of groundwater from pollution also have been widely developed in recent years. Among Russian researchers in this area should be noted the works of V.M. Goldberg , V.A. Mironenko, V.G. Rumynin, I.S. Zektser, A.P. Belousova, K.E. Pitieva , A.V. Lehov, I.K. Gavich, S.R. Krainov, J.S. Paszkowski, N.V. Rogovskaya, A.A. Roshal , V.M. Shvets, V.M. Shestakov, L.M. Rogachevskaya, I.V. Pozdnyakova, O.A. Karimova and many other.

Many approaches are currently used to assess the vulnerability of fresh groundwater within a territory. Most methods are based either on a qualitative or quantitative approach:

- A **qualitative** assessment of the territory is made according to the intensity of the impact of different natural and man-induced factors on the aquifers' vulnerability. This facilitates comparison of different parts of the territory from the point of view of their vulnerability.

- A **quantitative** assessment of the time (rate) for a certain possible contaminant to penetrate into the aquifer, accounting for natural properties of the waterbearing and overlaying rocks and the migration abilities of the contaminant.

In other words, there are two different approaches: ***intrinsic** and **specific***. The first is assessment and mapping of groundwater protective properties or vulnerability of any territory without taking into account characteristics and properties of certain contaminants. The second is assessing and mapping protective properties of a natural system as applied to a certain type of contamination (Zektser I.S., Everett L.G, 2000).

Estimation of groundwater vulnerability is based on the assessment of several parameters, which vary over regions as a function of the physical environment. The principal attributes used in groundwater vulnerability assessment (intrinsic and specific) are recharge, soil properties, and the characteristics of the unsaturated and saturated zone.

Recharge is the amount of water passing through the unsaturated zone into an aquifer during a specified period of time. Recharge is usually expressed as *annual net recharge*. The amount and mode of recharge significantly affect the physical and chemical processes in the soil-rock-ground water system, and ultimately the *attenuation* processes. Also needed are the climatic data, such as precipitation, air temperature, and evaporation that significantly influence the amount of recharge. However the importance of recharge varies with the change of climatic conditions. In arid zones recharge is very low and nil in hyperarid regions. In these regions groundwater vulnerability is very low. In semi-arid zones low recharge implies very slow movement of contaminants.

The *soil*, the upper unconsolidated layer of the earth's crust, is commonly regarded as one of the principal natural factors in the assessment of groundwater vulnerability. The main soil parameters related to vulnerability include texture, structure, thickness and the content of organic matter and clay minerals. The soil has an important attenuation function and represents the 'first line of defense' against contaminants moving from the surface toward the groundwater. However, the soil properties assessment should always take into consideration whether the soil in the area under study is in natural conditions or under the human stress.

The unsaturated zone's main feature is that it delays the arrival of contaminants to the groundwater table by a variety of chemical and physical processes. Then the character of the unsaturated zone (thickness, lithology, and vertical permeability) and its potential attenuation capacity decisively determine the degree of groundwater vulnerability. The thickness of the unsaturated zone depends on the position of the water table, which is not stable and fluctuates. For this reason, an analysis of groundwater level fluctuations should be included in vulnerability assessment and the highest elevation of the water table (the minimum thickness of the unsaturated zone) is used in vulnerability evaluation. If unsaturated zone is composed of low permeable rock, it creates a confining layer for the underlying aquifers and reduces significantly their vulnerability.

An *aquifer* (*the saturated zone*) is a heterogeneous system and its influence on groundwater vulnerability varies spatially and with depth. The definition of recharge and discharge areas and determination of semiconfined, confined and unconfined aquifer conditions is quite important and must always be considered when assessing its vulnerability. The main parameters for assessment of aquifer vulnerability include the aquifer nature and geometry, porosity, hydraulic conductivity, transmissivity, storage properties, and groundwater flow direction. The importance of hydraulic conductivity is emphasized. Fewer attenuation processes take place in the saturated zone where solution, dilution, and hydrodynamic dispersion would be the most important for the assessment of aquifer vulnerability.

From the attributes of secondary importance, topography, groundwater/surface water relation, and the nature of the underlying unit of the aquifer usually are included in vulnerability assessment. An important attribute is particularly topography, which influences amount of recharge, soil development, and groundwater flow direction and velocity (Zektser I.S., 2007).

The evaluation of the *specific vulnerability* of an aquifer should be made case by case, taking into account all the chemical and physical features of each single contaminant that is present (or of a group of similar contaminants), the type of source (punctual or diffused), quantity, means and rates of contaminant applications (Andersen L.J., Gosk E., 1987; Foster, 1987; Bachmat Y., Collin M., 1987). In comparison with the assessment of intrinsic vulnerability, which is based mostly on the static natural parameters of the soil-rock-groundwater system, the dynamic and variable parameters are included in the assessment of specific vulnerability. The contaminant's travel time in the unsaturated zone and its residence time in an aquifer are often introduced.

Two important considerations should be down when evaluating specific groundwater vulnerability: land use and population density (Zektser I.S., Everett L.G., 2004). There is a fundamental difference between areas with land under human stress (agriculture, industry, settlements, acid deposition) and areas where natural landscape with natural vegetation predominates (forests, uncultivated meadows, mountains regions). The more densely an area is populated, the greater the potential and real contaminant load on the ground- water system*)*.

The estimation of vulnerability taking into account characteristics and properties of concrete contaminants requires a substantial quantity of the physical data which reception is normally connected with high financial costs. In practice, the qualitative assessment of vulnerability is more often carried out, especially in regional scale. However, it should be noted that the full assessment of vulnerability of an aquifer and the risk of groundwater contamination can only be achieved through local research. Use of techniques of regional researches may reduce the number of areas to be studied in detail, by identifying the most vulnerable areas.

The results of groundwater vulnerability assessment can be used as an important tool in the process of solving environmental problems, interrelated with and integrated into master plans to support the planning, policy and strategy of groundwater resources protection and quality conservation.

The timely assessment of groundwater resources vulnerability prevents their qualitative alteration, deterioration or pollution. Vrba nouts (Vrba J., Zaporožec A., 1994), if groundwater vulnerability is not assessed in time, and groundwater use and protection strategy is not defined upon, then the costs of polluted groundwater recovery will be much higher than the cost of measures for its protection.

2.2 Analysis of methods of groundwater vulnerability assessment to contamination

Many different methods have been developed for assessing of groundwater vulnerability. These techniques vary considerably, according to the physiography of the tested areas, to the quantity and quality of the data, and to the aim of the study (Civita M., De Maio M., 2004).

The current international practices in mapping groundwater vulnerability have been reviewed by Vrba and Zaprozec (1994), Magiera (2000), Goldscheider (2002), Heinkele et al. (2002), Civita (1994) and others.

Vrba and Zaprozec (1994) divided the methods for estimating groundwater vulnerability into universal methods, which can be used for any physiographic conditions, and local methods, which can be used only for individual regions. These two classes, in turn, are divided into three basic groups (Civita M. , 1994); (Vrba J., Zaporožec A., 1994):

- Homogeneous area zoning (hydrogeologic complex and setting methods (HCS));

- Parametric System Methods (PSM): Matrix System (MR), Rating System (RS), Point Count System Models (PCSM).

- Analogical relations (AR) and numerical models methods

The hydrogeological complex and setting methods (HCS)

This kind of methods implies a qualitative assessment. First, one must decide the hydrogeological, hydrographical and morphological conditions that correspond to each class in a vulnerability scale. Then the entire area is analysed and divided following the criteria established (Albinet, M., Margat, J., 1970). Generally, a map overlay procedure is used. Large areas with various hydrographical and morphostructural features are best suited for assessment through these methods and thematic maps are produced from medium to large scale (Gogu R.C., Dassargues A., 2000).

As an example, the approach to assessment of groundwater vulnerability proposed by M. Civita (1990), named **GNDCI-CNR BASIC METHOD**. This method of definition of intrinsic vulnerability is based on some standard obtained in a result of superposition of several (about 20) hydrogeological settings that can be found in the Italian territory. This method is highly flexible and can be adapted, if necessary, to other situations that are not dealt with in the standard. The lithological, structural, piezometric and hydrodynamic indexes are not rigorously quantified. Starting from a complete examination of the main hydrogeologic settings, the representative sites are extracted from those that best define the settings. The main factors of the aquifer vulnerability (e.g. depth to groundwater, porosity, fracturing index, karst index, linkage between stream and aquifer, and so on) are identified for each site. As a result, the settings are distributed over the 6 degrees of intrinsic vulnerability (Table 2.1).

Table 2.1. Standards of Italian hydrogeologic settings (GNDCI-CNR basic method)

M. Civita (1990)

Vulnerability degrees	Hydrogeologic complexes and setting features
Extremely high	Unconfined (water table) aquifer in alluvial deposits: streams that freely recharge the groundwater body; well or multiple well systems that drawdown the water table to under the stream level (forced recharge). Aquifer in carbonate (and sulphate) rocks affected by completely developed karst phenomena (holokarst with high karst index [KI]).
Very high	Unconfined (water-table) aquifer in coarse to medium-grained alluvial deposits, without any surficial protecting layer. Aquifer in highly fractured (high fracturing index [FI]) limestone with low or null KI and depth to water <50m.
High	Confined, semiconfined (leaky) and unconfined aquifer with impervious (aquaculture) or semipervious (aquitard) superficial protecting layer. Aquifer in highly fractured (high fracturing index) limestone with low or null KI and depth to water >50m. Aquifer in highly fractured (but not cataclastic) dolomite with low or null KI and depth to water <50m Aquifer in highly clivated volcanic rocks and non-weathered plutonic igneous rocks with high FI.
Medium	Aquifer in highly fractured (but not cataclastic) dolomite with low or null KI and depth to water >50m. Aquifer in medium to fine-grained sand. Aquifer in glacial till and prevalently coarse-grained moraines.
Medium - Low	Strip aquifers in bedded sedimentary sequences (shale-limestone-sandstone flysch) with layer by layer highly variable diffusion rates. Multi-layered aquifer in pyroclastic non indurated rocks (tuffs, ash, etc.): different diffusion degrees layer by layer close to the change in grain size.
Low	Aquifer in fissured sandstone or/and non carbonatic cemented conglomerate. Aquifer in fissured plutonic igneous rocks. Aquifer in glacial till and prevalently fine-grained moraines. Fracture network aquifer in medium to high metamorphism rock complexes.
Very low or null	Practically impermeable (aquifuge) marl and clay sedimentary complexes (also marly flysch): contamination directly reaches the surface waters. Practically impermeable (aquifuge) Fine-grained sedimentary complexes (clay, silt, peat, etc.) contamination directly reaches the surface waters. Meta-sediment complexes or poorly fissured highly tectonized clayey complexes low metamorphism complexes, almost aquifuge: contamination directly reaches the surface waters.

The parametric methods

The parametric methods include Matrix Systems (MS); Rating Systems (RS) and Point Count System Models (PCSM).

The overall procedure for all of these systems is the same. It begins with the selection of parameters judged to be representative for vulnerability assessment. Each of the selected parameters has a given range, which is subdivided into discrete hierarchical intervals. Each interval is assigned a value reflecting the relative degree of vulnerability, and the rating points are summed. The final numerical score is divided into segments expressing a relative vulnerability degree.

Matrix Systems methods are based on a restricted number of carefully chosen parameters. To obtain a quantified degree of vulnerability, these parameters are combined following a number of strategies developed by different research groups. These research applications are site-specific methods developed for local case studies, such as the method selected for the Flemish Region of Belgium (Goossens M., Van Damme M., 1987*)* and the system used by Severn-Trent Water Authority in some areas of Central England (Carter and others 1987).

Point Count System Models or Parameter Weighting and Rating Methods (PCSM) are also a rating parameters system. Additionally, a multiplier identified as a weight is assigned to each parameter to correctly reflect the relationship between the parameters. Rating parameters for each interval are multiplied accordingly with the weight factor and the results are added to obtain the final score. This score provides a relative measure of vulnerability degree of one area compared to other areas and the higher the score, the greater the sensitivity of the area. One of the most difficult aspects of these methods with chosen weighting factors and rating parameters remains distinguishing different classes of vulnerability (high, moderate, low etc.), on basis of the final numerical score (Gogu R.C., Dassargues A., 2000). Examples are the DRASTIC method developed by U.S. EPA in 1985 (Aller, L.T. et al., 1987), SINTACS method (Civita M. , 1994), and the EPIK method used in karst groundwater protection strategy developed by Doerfliger and Zwahlen (1997).

DRASTIC

The DRASTIC methodology was developed in the United States under cooperative agreement between the National Water Well Association (NWWA) and the USA Environmental Protection Agency (EPA). The procedure was designed to provide for systematic evaluation of groundwater-pollution potential in any hydrogeologic setting.

The DRASTIC method considers seven parameters, which taken together, provide the acronym:

D - Depth to water table

R - net Recharge

A - Aquifer media

S - Soil media

T - Topography

I - Impact of the vadose zone media

C - hydraulic Conductivity of the aquifer

The system contains three parts: 1) weights; 2) ranges; and 3) ratings (Aller et al., 1987). Each DRASTIC parameter has been assigned a relative weight between 1 and 5, with 5 being considered most significant in regard to contamination potential and 1 being considered least significant. DRASTIC has two sets of weights: one for pollutants in general and one for pesticides (Table 2.2). Depth to Water and Impact of the vadose zone media are considered to be the most important factors and have the weight of 5, whereas Topography is the least important with the weight of 1.

Table 2.2. Assigned weights for DRASTIC parameters (Aller et al., 1987)

Parameters	General weight	Pesticide weight
Depth to Water Table	5	5
Net Recharge	4	4
Aquifer Media	3	3
Soil Media	2	5
Topography	1	3
Impact of the vadose zone	5	4
Hydraulic Conductivity	3	2

In turn, each of the parameter is "sub-divided" into either numerical ranges (e.g., depth to water in feet) or media types (e.g., materials making up a soil) which impact pollution potential. Table 2.3 illustrates the ranges and ratings for soil media. Finally, the ratings are used to quantify the ranges/media with regard to likelihood of groundwater pollution.

The final result for each hydrogeologic setting (i.e. geographic area) is a numerical value obtained using the following simple equation:

$$\text{DRASTIC INDEX} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw \quad (2.1)$$

where : D, R, A, S, T, I and C are the parameters, r – rating, w – weight.

Table 2.3. Ranges and ratings for soil media (Aller et al., 1987)

RANGE	RATING
Gravel	10
Thin or absent	10
Sand	9
Peat	8
Shrinking and/or Aggregated Clay	7
Sandy Loam	4
Loam	5
Silty Loam	4
Clay Loam	3
Muck	2
Nonshrinking and Nonaggregated Clay	1

The higher the DRASTIC index value, the greater the groundwater pollution potential and aquifer vulnerability.

The DRASTIC method was developed using 4 assumptions (Al-Zabet, 2002):

1. the pollutant is introduced at the ground surface
2. the pollutant is flushed into the groundwater by rainfall
3. the pollutant has the velocity of water
4. the area evaluated using DRASTIC is 40 hectares or larger.

These conditions limit the possibility of application of this method for assessment of vulnerability.

The major drawback of this method is the subjectivity of the determination of the rating scale and the weighting coefficients. Doubts have also been expressed for the selection of the specific parameters and the exclusion of others points (Panagopoulos G.P. et al, 2006).

In brief, the DRASTIC method has been criticized on the following:

- So many variables are factored into the final index that critical parameters in groundwater vulnerability may be subdued by other parameters that have no bearing on vulnerability for a particular setting (Vrba J., Zaporožec A., 1994); (Merchant, 1994).

- The selection of the parameters is based on qualitative judgment and not quantitative studies (Garrett et al. 1989).

- Many important scientifically defined factors, e.g. sorption capacity, travel time and dilution are not taken directly into account (Rosen, 1994).

Despite these criticisms, many advantages of the DRASTIC and similar other methods have been recognized:

- The method has a low cost of application and can be applied in extensive regions, because of the relatively few, and easy to collect, data required (Aller et al., 1987).

- The selection of many parameters and their interrelationship decrease the probability of ignoring some important parameters, restrict the effect of an incidental error in the calculation of a parameter and so enhance the statistical accuracy of the model (Rosen, 1994).

- This method gives relatively accurate results for extensive regions with a complex geological structure, despite the absence of measurements of specific parameters that the most specialized methods would require (Kalinski et al. 1994; McLay et al., 2001).

But, as Aller et al. (1987) warn, "the DRASTIC Index provides only a relative evaluation tool and is not designed to provide absolute answers." Thus, one must understand that DRASTIC was intended as a reconnaissance tool, but has proven its value as an indicator of areas deserving a detailed hydrogeologic evaluation.

SINTACS

The SINTACS method (Civita M., 1994; Civita M., De Maio M., 2000), originally derived from DRASTIC, in the latest release 5, retains only the structure of DRASTIC. The acronym SINTACS comes from the Italian names of the factors that are used:

S - Soggicenza (depth to groundwater)

I - Infiltrazione (effective infiltration)

N - Non saturo (unsaturated zone attenuation capacity)

T - Tipologia della copertura (soil/overburden attenuation capacity)

A - Acquifero (saturated zone characteristics)

C - Conducibilita (hydraulic conductivity)

S - Superficie topografica (topographic surface slope)

When the factors that are used to assess the aquifer vulnerability to contamination are selected; a subdivision into value intervals and/or declared types is applied to each selected factor; a progressive rating (ranging 1 – 10) is given to each interval as a function of the importance in the final assessment; the selected ratings of each factor must be multiplied for a choice of weight (W) strings, which are used in parallel and not in series, each one describing a hydrogeologic and impact setting that emphasizes the action of each parameter (Civita M., De Maio M., 2004). More detailed description of factors and their ranking according to the degree of impact on vulnerability are presented in Chapter 5.

The final intrinsic vulnerability (SINTACS indicator) is expressed by the following formula:

$$I_{SINTACS} = SrSw+IrIw+NrNw+TrTw+ArAw+CrCw+SrSw \quad (2.2)$$

where **r** is the “rating value” - mark, **w** is the “weight” – weight associated to each parameter.

Although the formula and the parameters used for SINTACS are identical to the method of DRASTIC, SINTACS has more flexibility in definition of ratings and weights. The biggest difference between the methods SINTACS and DRASTIC consists in estimation of landscape disturbance as a factor affecting the vulnerability of groundwater.

As this method takes into account the different conditions of the disturbance, application of this method on territory with various geological environments is quite common (Corniello et al., 2004; Cusimano G. et al., 2004; Kuisi AV, 2006). The advantage of method SINTACS is that it allows to observe fractures in rocks and presence of karst processes that affect water flow and a contaminant distribution in the subsoil. However, this method does not solve the constraints considered in the analysis of DRASTIC method.

EPIK

The EPIK method has been specifically created for the vulnerability assessment of the karst aquifers *(*Doerfliger N. and Zwahlen F., 1997; Doerfliger N. et al., 1999) in Switzerland. Four main parameters are considered and mapped: epikarst (E), protective cover (P), infiltration conditions (I), and karst network development (K). The E parameter considers the effects in terms of water storage (during rainfall or snow melt) and of the concentration of flow toward vertical conduits; it is assessed on the basis of geomorphological maps considering three sub-parameters. The P parameter describes the protective function of the layers between the ground surface and the groundwater table, mainly soil, subsoil, non-karst rock, and unsaturated karst rock. The I parameter is assessed by distinguishing concentrated infiltration areas and areas in which diffuse infiltration prevails, where the slope and land use are the key sub-factors. K represents the degree of karst network development in the *aquifer* (Polemio M. et al, 2009).

According to this method the karst groundwater vulnerability is evaluates bringing forward complexity classes and weighting coefficients for the appraised parameters. The classification for each parameter and area is obtained by systematic mapping for these parameters. The class values for the EPIK parameters are shown in table 2.4, while table 2.5 illustrated the weighing coefficients for the EPIK parameters.

For each analyzed class of parameters, the assessment is made by the class value, multiplied with a weighting coefficient (α, β, γ, δ), specific to the protective function of every parameters. After adding all data, the final result provides the protection factor (F), showing therewith the groundwater vulnerability degree. The bigger the sum, the smaller vulnerability value of the referred area is. The vulnerability assessment can be achieved by following the next formula, a simplified hydrogeological model:

$$F = (\alpha \cdot E) + (\beta \cdot P) + (\gamma \cdot I) + (\delta \cdot K) \quad (2.3)$$

Table 2.4. The class values for the EPIK parameters

Epikarst			Protective cover				Infiltration conditions				Karst network development		
E_1	E_2	E_3	P_1	P_2	P_3	P_4	I_1	I_2	I_3	I_4	K_1	K_2	K_3
1	3	4	1	2	3	4	1	2	3	4	1	2	3

Table 2.5. The relative values of the weighting coefficients (α, β, γ, δ)

Parameter	Epikarst (E)	Protective cover (P)	Infiltration conditions (I)	Karst network (K)
Weighing coefficient	α	β	γ	δ
Relative weight	3	1	3	2

The F factor ranges from 9 to 34 and it is ranked in four classes of vulnerability: very high (9–20), high (20–25), moderate (25–30) and low (30–34). The classes can be labelled on the basis of the logical low protection-high vulnerability criterion: a protection factor of 34 indicates the highest protection and also a very low or minimum vulnerability.

The method requires a detailed evaluation of karst features, which is often difficult, costly and time consuming as they involve field studies, geophysics, isotope studies, hydrologic studies, an analysis of the hydraulic character, etc. The detection of typical karst features like swallow hole and sinks often requires the interpretation of aerial photograph or high resolution satellite images (Margane, 2003).

Rating Systems (RS) methods provide a fixed range of values for any parameter considered to be necessary and adequate to assess the vulnerability. This range is properly and subjectively, divided according to the variation interval of each parameter. The sum of rating points gives the required evaluation for any point or area. The final numerical score is divided into intervals expressing a relative vulnerability degree. The rating systems are based upon the assumption of a generic contaminant (Gogu R.C., Dassargues A., 2000). Examples are GOD system (Foster, 1987), AVI Method (Van Stempvoort et al., 1993), and the ISIS method (Civita M., De Regibus C., 1995).

GOD

GOD (Foster, 1987) is a rating system method that assesses vulnerability by means of three variables: groundwater occurrence (G), overall lithology of aquifer (O) and depth to groundwater table (D). This method uses fewer parameters than DRASTIC and SINTACS, although two of them (G and D) also depend on the lithology and the range of values for each rating is short, varying from 0 (minimum vulnerability) to 1 (maximum vulnerability). The final index is obtained from the formula:

$$I = G \cdot O \cdot D \quad (2.4)$$

The value of the index may vary from 0 to 1 and five vulnerability classes are differentiated by the method.

Fig. 2.1 illustrates the concept of creating a GOD vulnerability map.

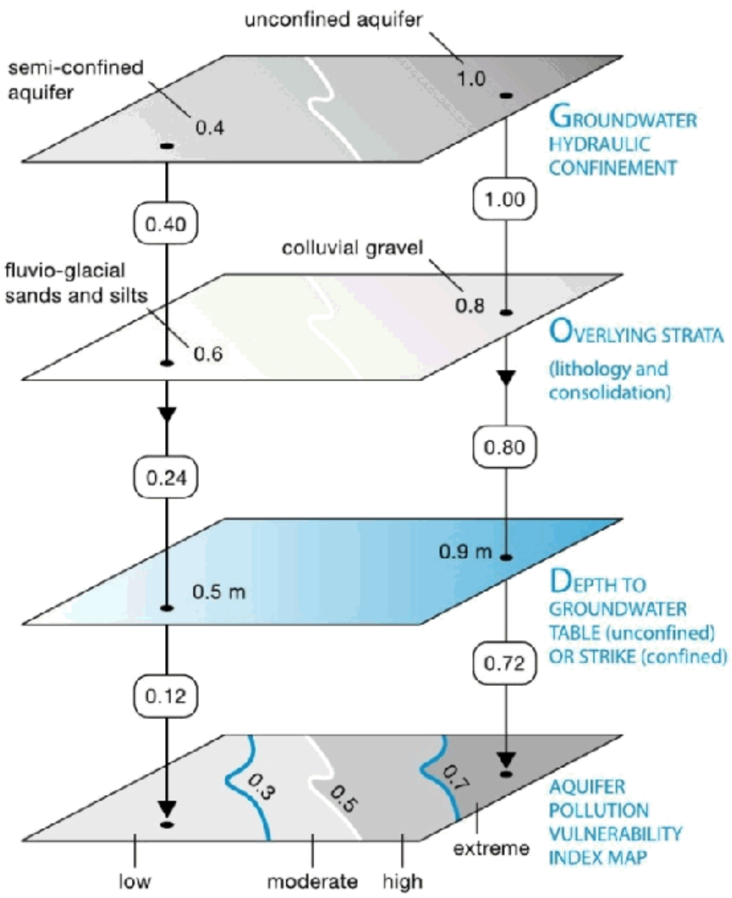


Figure 2.1. Generation of an aquifer vulnerability map using the GOD method (Foster et al., 2002)

Following the GOD flowchart, the area vulnerability index is computed by choosing first the rating of groundwater occurrence parameter and then multiplying by the overlying lithology rating as well as with the depth to water parameter rating. The overlying lithology parameter contributes to the vulnerability index only in the case of unconfined aquifers. Because the parameters can only take values from 0 to 1, the computation result is usually a value less than the score assigned to each parameter. In the particular case where two parameters have a value equal to 1, the vulnerability score is equal to the score of the third parameter (Gogu R.C., Dassargues A., 2000).

The advantage of GOD method consists in its relative simplicity. Besides, a small number of parameters means less subjectivity. In comparison with the method SINTACS, the factor of groundwater recharge, in the method GOD, has more weight (Zao X.V., 2005).

Disadvantage of GOD are, first of all, insufficient consideration of the factor of soil. Use of this calculation scheme means that the parameter with the lowest value has a greater effect on the final assessment, especially if the other two parameters have a value of 1. In contrast to the DRASTIC and SINTACS this method only takes into account factors related to the unsaturated zone (Zao X.V., 2005).

Thanks to the simple and pragmatic structure this method could be recommended for vulnerability assessment on large areas (used in land management).

AVI

This method (Van Stempoort et al. 1993) estimates the aquifer vulnerability index (AVI) using only two parameters: the thickness of each sedimentary layer above the uppermost saturated aquifer (d) and the estimated hydraulic conductivity (k) of each of these layers. This method does not consider ratings and/or weights.

The index is determined from the relation between the two parameters, taking into account variations of an order of magnitude, according to the following equation:

$$c = \sum_{i=1}^{n} \frac{d_i}{k_i} \qquad (2.5)$$

where

c = hydraulic resistance

d - thickness of layers sedimentary unit above the uppermost aquifer

k - estimated hydraulic conductivity of each of the n layers

n - the numbers of layers

The final result calculated by the formula AVI is called "hydraulic resistance" and characterize the time of travel of contaminant to aquifer.

The c or log (c) value is related to a qualitative Aquifer Vulnerability Index by a relationship table (table 2.6). The authors suggest calculating c for each well or test hole and then to generate the isoresistance contour to classify the study area in AVI zones (Gogu R.C., Dassargues A., 2000).

Table 2.6. Vulnerability index for AVI method

Hydraulic resistance (years)	*Log c*	Vulnerability index AVI
0-10	<1	very high
10-100	1-2	high
100-1,000	2-3	medium
1,000-10,000	3-4	low
>10,000	>4	very low

The AVI method requires detailed data on the structure of the unsaturated zone. It means that this method might be use only if there is a network of wells with data on the geological structure of the investigated area. Although, the value of hydraulic resistance (*c*) does not fully describe the time of travel of pollutants, the calculations of hydraulic resistance can solve the problem on a basis of measurable characteristics of the geological environment, and not on a basis of empirical solutions, like in the DRASTIC method.

It should be noted that the use of a logarithm for separation degree of groundwater vulnerability does AVI, as well as DRASTIC, of this method to distinguish of hydraulic resistance with lower values.

ISIS

This method is a synthesis of various studies on aquifers intrinsic vulnerability assessment (Civita M., De Regibus C., 1995) and can be classed with *the rating systems* group of methods. ISIS is a hybrid method, based on the comparative evaluation of the existing hydrogeological situations. It has been developed taking into account the rating and weighting systems of DRASTIC and SINTACS methods and the GOD method for the general structure design. Parameters used by ISIS method are: the annual mean of the net recharge (it is possible to introduce the rainfall value and the mean annual temperature or other related parameters), topography, soil type, soil thickness, lithology of the unsaturated zone, thickness of the unsaturated zone, aquifer medium, and aquifer thickness.

The land-use parameter, as the human activity impact feature, has been adopted from the SINTACS methodology and quantified. It has been divided in three areal units: areas with normal conditions, strong contaminated agricultural area, strong superficial drained area. This parameter is used as a weighting element for modulating the relative importance of the direct used parameters, as a function of the different land use conditions (Gogu R.C., Dassargues A., 2000).

To estimate the vulnerability index I_v, ISIS method is using the following formula:

$$I_v = p_{Inf} \times f_{Inf} + p_{Su} \times f_{Sus} \times f_{Su} + p_{Ins} \times f_{Si} \times f_{Ins} + p_{Sat} \times f_{ss} \times f_{Sat} \quad (2.6)$$

where:

p_{Inf} - the rating values for ranges on the net recharge;

f_{Inf} - infiltration coefficient dependent on land use;

p_{Su} - the rating values for the soil media;

f_{Sus} - soil coefficient dependent on land use;

f_{Su} - weighting coefficient dependent on soil thickness;

p_{Ins} - the rating values assigned to the vadose zone;

f_{Si} - weighting coefficient dependent on the unsaturated zone lithology and thickness;

f_{Ins} - vadose zone coefficient dependent on land use;

p_{Sat} - the rating values assigned to aquifer media;

f_{ss} - weighting coefficient dependent on the aquifer thickness;

f_{Sat} - aquifer coefficient dependent on land use.

The final vulnerability index, varying between 24 and 180 is divided in 6 vulnerability classes: extreme (141–180); very high (124–140); high (88–123); medium (64–87); low (44–63); very low (24–43).

As this method pays much attention to land use of investigated territory the results obtained by this method give more accurate index of groundwater vulnerability in those areas where human activity is more intensive.

Analogical relations (AR) and numerical models methods

These methods of *quantitative assessment* are a narrowly defined category of methods generally applicable for the assessment of specific vulnerability only. These methods require contaminant specific and site-specific data. The application of models is useful for small areas where vulnerability to contamination shall be assessed (Zektser I.S., Everett L.G., 2004).

Analogical relations (AR) are based on mathematical standard descriptions of hydrological and hydrogeological processes (e.g. transport equations) that are analogously used to assess the groundwater vulnerability. Moreover, the essence of this approach is that the effect of certain analog devices reproduces some hydrogeological processes on the model (such as filtration, drying, or saturation, etc.). For example, the process of water filtration in a porous medium can be modeled by means of electrical resistance, since the processes of water filtration and movement of electric current can be described by the same equations in terms of mathematics (Darcy's law for water filtration in a porous medium and Ohm's law of electrical current)

(Gavich, 1988).

Magiera P. (2000) describes 13 methods of that type. Most of them are used for the evaluation of the specific vulnerability of groundwater to pesticides on a large to medium scale.

Numerical Models (flow and transport models for the unsaturated and saturated zone) are a group of method which defines behavior and transport of pollutants for certain areas. In its basis the fundamental equations unite the numerous chemical, biological and physical processes affecting groundwater vulnerability. Magiera P. (2000) describes nine examples for the application of mathematical models for specific vulnerability mapping on a large to medium scale. Those models take into account the properties of the contaminant (mostly nitrates and pesticides) and the properties of the overlying layers. For the preparation of maps reflecting the specific groundwater vulnerability such methods will certainly play a major role in the future because only combined groundwater flow and transport models will be able to deal with the large quantity of the various input data required for such maps. A vast number of other numerical models have been established to simulate the transport of certain substances through the unsaturated zone, such as the pesticide leaching model used by Holtschlag & Luukonen (1997).

I would also like to dwell on the approach to the assessment of the degree of groundwater protection developed in the All-Russian Research Institute for Hydrogelogy and Engineering Geology (VSEGINGEO) in the mid-1980s by V.M. Goldberg and S. Gazda (1984). This approach is still widely used in Russia for compiling maps of the degree of protection of subsoil and confined waters.

The degree of groundwater protection against pollution is understood as the presence of deposits, first of all, low-permeability deposits, overlying the aquifer and preventing pollutants from penetrating from the land surface to the groundwater (Goldberg,V.M., Gazda,S., 1984).

A two-stage estimate is considered most reasonable.

The first-stage studies (regional studies aimed at purely qualitative estimation of the degree of protection) should be focused on the natural factors determining groundwater protection, such as the presence of low-permeability deposits in the geological section; the depth of groundwater occurrence; the thickness, lithological properties, and hydraulic conductivity of rocks, first of all, lowpermeability rocks; sorption characteristics of the rocks; and the relationship between the heads in the aquifers.

At the second stage (detail studies associated with concrete facility designs and problems of economic development of lands, which require quantitative estimates), anthropogenic physicochemical factors should be taken into account in addition to the natural factors.

The qualitative estimates of the degree of groundwater protection (at the regional level) is based on the sum of points determined by the depth to groundwater table (aeration zone thickness), the thickness of low-permeability deposits, and their lithological characteristics, which reflect the hydraulic conductivity of these deposits (Goldberg,V.M., Gazda,S., 1984).

Each factor has certain graduation and respective points. The depth of groundwater table is subdivided into five intervals (table 2.7) and each interval has its own respective points. The points value for the factor "thickness of low-permeability deposits" varies depending on its intervals (in m) and lithological characteristics (table 2.8). According to the lithology and filtration properties the deposits are subdivided in 3 groups: **a** – loamy sand, sandy loam (k = 0,1 – 0,01 m/day), **c** – clay loam, clay (k <0,001 m/day), и **b** – a mixture of rock of groups a и c (k = 0,01 – 0,001 m/day).

Table 2.7. Depth of groundwater table and the respective points

Depth of groundwater table (H), m	$H \leq 10$	$10 < H \leq 20$	$20 < H \leq 30$	$30 < H \leq 40$	$H > 40$
points	1	2	3	4	5

The degree of groundwater protection is determined by the sum of points. There are six categories of groundwater protection (table 2.9).

Table 2.8. The thickness of low-permeability deposits in unsaturated zone, their generalized lithologic characteristics, and the respective points

Thickness of low-permeability deposits (m_0), m	*Lithologic* groups		
	a	*b*	c
	points		
$m_0 \leq 2$	1	1	2
$2 < m_0 \leq 4$	2	3	4
$4 < m_0 \leq 6$	3	4	6
$6 < m_0 \leq 8$	4	6	8
$8 < m_0 \leq 10$	5	7	10
$10 < m_0 \leq 12$	6	9	12
$12 < m_0 \leq 14$	7	10	14
$14 < m_0 \leq 16$	8	12	16
$16 < m_0 \leq 18$	9	13	18
$18 < m_0 \leq 20$	10	15	20
$m_0 > 20$	12	18	25

Table 2.9. The categories of groundwater protection degree

Categories of groundwater protection	I	II	III	IV	V	VI
Sum of points	$\Sigma \le 5$	$5 < \Sigma \le 10$	$10 < \Sigma \le 15$	$15 < \Sigma \le 20$	$20 < \Sigma \le 25$	$\Sigma > 25$

Higher category of protection corresponds to the large sum of points. The lowest category of protection corresponds to I category, the highest - VI category.

The quantitative estimate of the degree of protection of subsoil water is performed by calculating the time (t) required for the polluted water, filtering from a land surface, to reach the groundwater level. The time is calculated in two ways: for filtration of polluted water from surface water basins with a constant level of water and for conditions of dumping of polluted waters on the land surface with a constant discharge.

In the first case the time of filtration (t_1) through 10-metre vadose zone composed by permeable rocks *(K =2 m/day)* is taken as a unit of point assessment:

$$t_1 = \frac{nH_0}{K}\left[\frac{m}{H_0} - \ln\left(1 + \frac{m}{H_0}\right)\right] \quad (2.7)$$

where n – porosity of rock in an unsaturated zone; H_0 - Altitude of a layer of wastewater in a storage; K,m – respectively, the hydraulic conductivity and thickness of the unsaturated zone.

In the second case, depending on a relationship of carrying capacity of a underlying stratum and the chosen calculated value of the specific discharge of groundwater (q), the time of a filtration of polluted water from a land surface is defined by following relations:

$$\text{if } q \le K \quad t = \frac{nm}{\sqrt[3]{q^2 K}} \quad (2.8)$$

$$\text{if } q > K \quad t = \frac{m}{\frac{(1-n)}{2n} + \sqrt{\frac{(1-n)^2 K^2}{4n^2} + \frac{qK}{n}}} \quad (2.9)$$

Thus, quantitative estimate of groundwater protection by this method is possible only in the presence of information about the average filtration properties of rocks in the unsaturated zone and about the conditions of presence or inflow of pollutants.

Methods of quantitative estimate of the degree of confined waters protection (Goldberg, 1987) allows to determine the time of pollutant penetration through a layer of overlying low-permeable deposits. To determine the time at each design point (cell) the following formula is proposed:

$$t = \frac{m_0^2 n}{K_0 \Delta H} \quad (2.10)$$

Where m_0 – thickness of a low-permeable stratum; n – active porosity (effective porosity); K – hydraulic conductivity; ΔH- difference of pressures in the investigated and overlying aquifer.

Characterizing this concept as a whole, it must be admitted that it has some benefits, but some drawbacks should also be mentioned. First of all, the range of protection factors taken into account is limited (in particular, it does not include the infiltration recharge of the aquifer) and the processes of sorption and radioactive decay are not considered in the estimation of groundwater protection either at the qualitative or at the quantitative level (Belousova, 2003).

Comparison of different methods of groundwater vulnerability assessment application to the same territory has been made by some scientists (Civita and De Regibus (1995); Gogu R.C., Dassargues A., 2000, 2003; Vias J.M.et al, 2005, and other).

Civita and De Regibus (1995) performed a significant comparative study of six methods of groundwater vulnerability assessment. To cover different hydrogeological situations, the study targeted three specific areas in Northern Italy, respectively flat, hilly and mountainous regions. The methods considered were DRASTIC, SINTACS, GOD, the Flemish Method (Goossens M., Van Damme M., 1987), ISIS, and the CNR – GNDCI method. Applying different methods to the same zone and using the same data showed that the relatively simple methods could provide similar results to the complex ones. It could be confirmed that these methods (as GOD for example) are best suited for designing large areas (used in land management). Having a good precision and flexibility, DRASTIC and SINTACS methods are much more effective in detailed studies.

One another case where an attempt has been made to compare methods was by an Italian research team in “Piana Campana” region, Southern Italy (Corniello et al., 1997). To assess the vulnerability of the aquifer in this area, four methods were tested: DRASTIC, SINTACS, GOD, and the AVI model. It was shown that the SINTACS method, compared with the others, generates “very high vulnerability zones in the areas concerned with surface waters and aquifer interactions. This result is strongly influenced by the aquifer identification and by different weight classification series used for the area affected by drainage.

In areas where the degree of vulnerability has modest variations, the GOD method provided homogeneous distributions of values. In consequence this method can only be used in areas with high contrasted vulnerability. Even with fewer parameters, the vulnerability map generated through AVI method was similar to those obtained from DRASTIC and SINTACS models.

Moreover, a statistical comparison of all vulnerability maps showed the greatest similarity between the DRASTIC and SINTACS methods as well as a good correlation between those two and the AVI method (Gogu R.C., Dassargues A., 2000).

The comparison of different methods shows that the choice of the most appropriate method for groundwater vulnerability mapping to be used in a certain area depends on the data availability, spatial data distribution, the scale of mapping, the purpose of the map and the hydrogeological setting.

For example, in areas where data availability is low but the general hydrogeological setup is known, DRASTIC end SINTACS would be suitable methods of choice, since it is rather simple. If not all required parameters are known, it may be considered using an even more simple method, such as GOD. In pure karst environments, however, the application of EPIK is more recommended because it was specifically designed for this purpose.

Methods of vulnerability assessment can be applied both separately and in integration. Integrated use of different approaches to the assessment of groundwater vulnerability allows to solve successfully the assigned tasks, both at regional and local levels, even in the conditions of scarcity of information available to researchers. It is also advisable to carry out a vulnerability assessment in two stages, first by giving a regional (qualitative) assessment, and then a more detailed (quantitative) research with regard to concrete facility designs and land use problems. The UK National River Authority recognised that a full assessment of aquifer vulnerability and groundwater pollution risk can only be achieved by local studies (Robins et al, 1994). The qualitative methods can reduce the number of areas to be studied in detail by identifying the most vulnerable areas.

As Belousova A.P. (2003) notes, the diversity of methods for assessing groundwater protection against pollution demonstrates the significance of such studies for the environmental estimation of groundwater state and shows that these methods cannot be reduced to a single universal procedure.

CHAPTER 3

GENERAL CONDITIONS AND FACTORS OF FORMATION OF GROUNDWATER NATURAL VULNERABILITY TO POLLUTION OF THE UPPER KAMA POTASSIUM SALT DEPOSIT'S TERRITORY

The research territory (with area 2500 km^2) is located within the eastern margin of the East European Plain, in the upper reaches of the river of Kama (Figure 3.1).

There are two large administrative centers on the analyzed territory: the cities of Solikamsk and Berezniki. The number of population inhabiting Berezniki is equal to 156 thousand (2011) people, and is equal to 97 thousand people (2011) for Solikamsk. The major part of the population is employed in the industry. The main branches are the mining industry and the chemical industry. The mining industry is represented by six mining departments of Solikamsk and Berezniki (BPMD-2, BPMD-3, BBF-4, SPMD-1, SPMD-2, SPMD-3) of the Upper-Kama deposit of potassium salts.

Hundreds of articles of chemical products are produced on the enterprises of Berezniki and Solikamsk: potash and nitrogen mineral fertilizers, soda ash and caustic soda, pesticides, colorants, acids (Berezniki chemical plant, Berezniki soda plant, Berezniki nitrogen fertilizer plant, Solikamsk plant "Ural").

The Berezniki titanium-magnesium complex and the Solikamsk magnesium plant are large enterprises specialized in non-ferrous metals.

Seven oil deposits are known in the area of works. The largest of them is the Unvinskoe deposit. There are a network of oil and gas pipelines that stretch across the area.

Other active plants are the following: Solikamsk pulp and paper plant, Solikamsk timber procurement plant and Berezniki woodworking plant.

The building industry is represented by the following enterprises: Berizniki silicate and construction materials plant, Berezniki large panel homebuilding plant, Berezniki ferroconcrete constructions plant, building and construction departments of Berezniki and Solikamsk, "Bereznikikhimstroi" trust.

In agriculture, livestock farming predominates (Solikamsk broiler plant, "Polovodovskiy" stock-breeding complex). On the fields there are cultivated leguminous plants, large areas are occupied by potatoes, vegetables and feed crops.

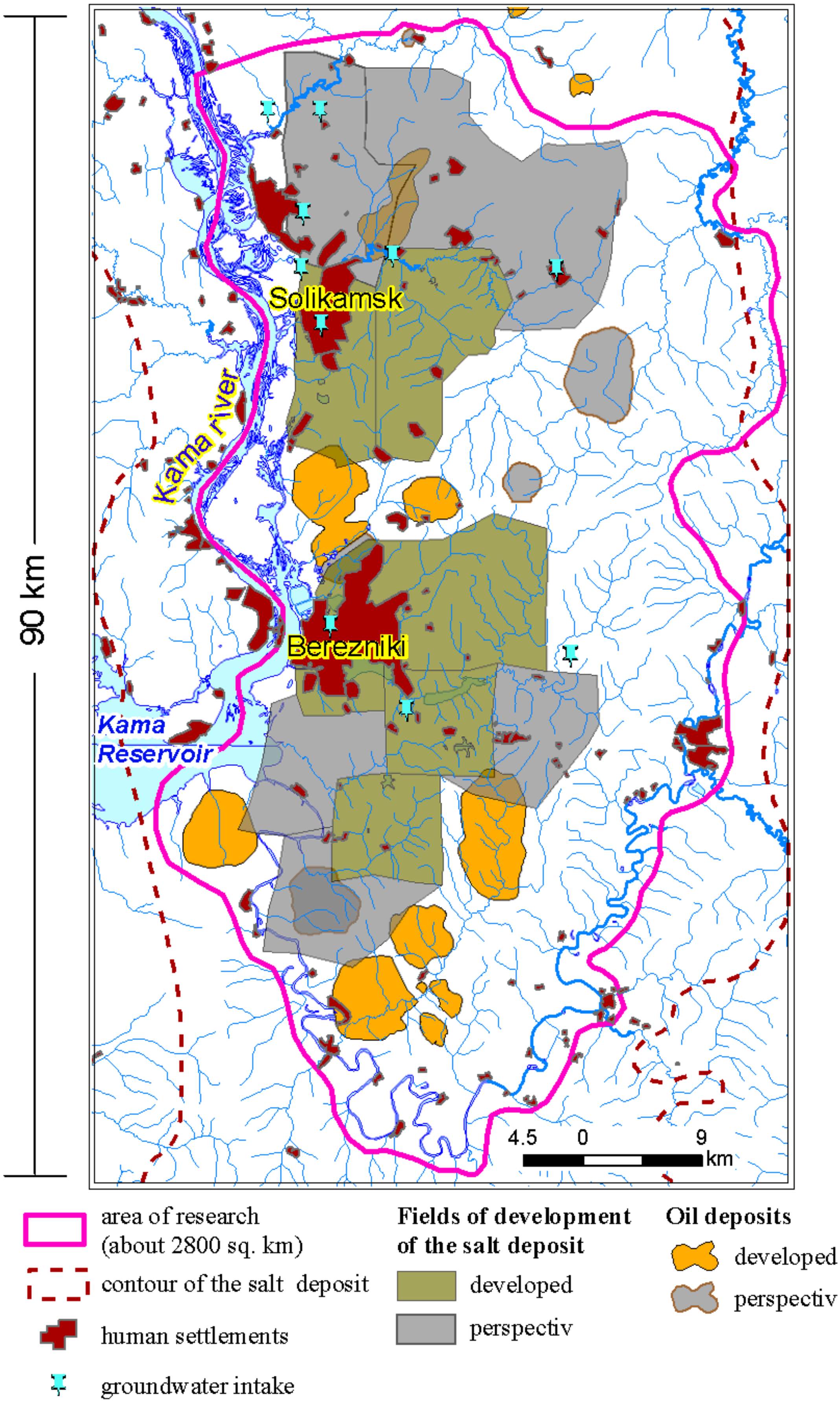


Figure 3.1. Situation plan of the study area

3.1. Relief

The relief of the region is divided into two orographical zones, according to the degree of ruggedness and altitude (Figure 3.2):

a) low accumulative plain which includes the valley of Kama river and the areas of lower valleys of its tributaries up to the absolute elevation +120 m;

b) elevated denudation plain, disconnected with a wide network of ravines, valleys of streams and small rivers. The absolute elevations are within +120 - +255 m.

The general rise of the territory is observed from the west to the east. The maximum altitude is equal to +255,0 m. The minimum altitude is equal to +108,2 m.

The relative elevation of watersheds above valleys varies from 40 m to 100 m. The passage to the watersheds is gradual. The most frequent altitude lies within the range of 108 - 120 m above sea level (Figure 3.3).

The research territory refers to a region of the Russian Plain, the denudation plain of the Preduralie, and represents a hilly plain drained by numerous watercourses of different order. The Kama water storage basin is located on the west.

Among the relief forms there are alluvial, paludal and karstic ones.

<u>The alluvial forms of relief</u> are widespread on the studied territory. Their morphology is different and depends on: a) the order of a plain, b) its structure position, c) the age of a plain.

The valleys of small watercourses have the simplest landscape. Their lengths vary from 1 to 5 km and width vary within 300 m. As a rule, they are not developed and are on the phase of active development, have a slightly developed trough-shaped transversal profile, which is typical for watercourses of the platform regime. The lithology of the dissolutioned bedrocks has a great influence on the morphology of these valleys. The age of the valleys is the newest.

The valleys of watercourses of higher orders (the rivers of Borovaya, Usolka, etc.) are more mature and developed. A complex of flood-plain terraces and above flood-plain terraces are marked out in these valleys. The valleys have a trough-shaped transversal profile with flat bottom. The time of initiation of these valleys formation refers to the end of the Pleistocene.

The largest valleys on the studied area are the valleys of the Yayva and the Kama rivers. These are large geomorphological units which initiated their formation in the Paleogene. During the long time of their evolution there were developed the broad flood valleys with full complex of terraces.

<u>The paludal forms</u>. Swamping and bog formation are the prevailing processes on the research territory. According to the conditions of bog formation and character of their spreading, several varieties can be marked out (bogs on watershed and slopes; bogs formation in valleys; bogs of inter-ridge depressions and bottomland).

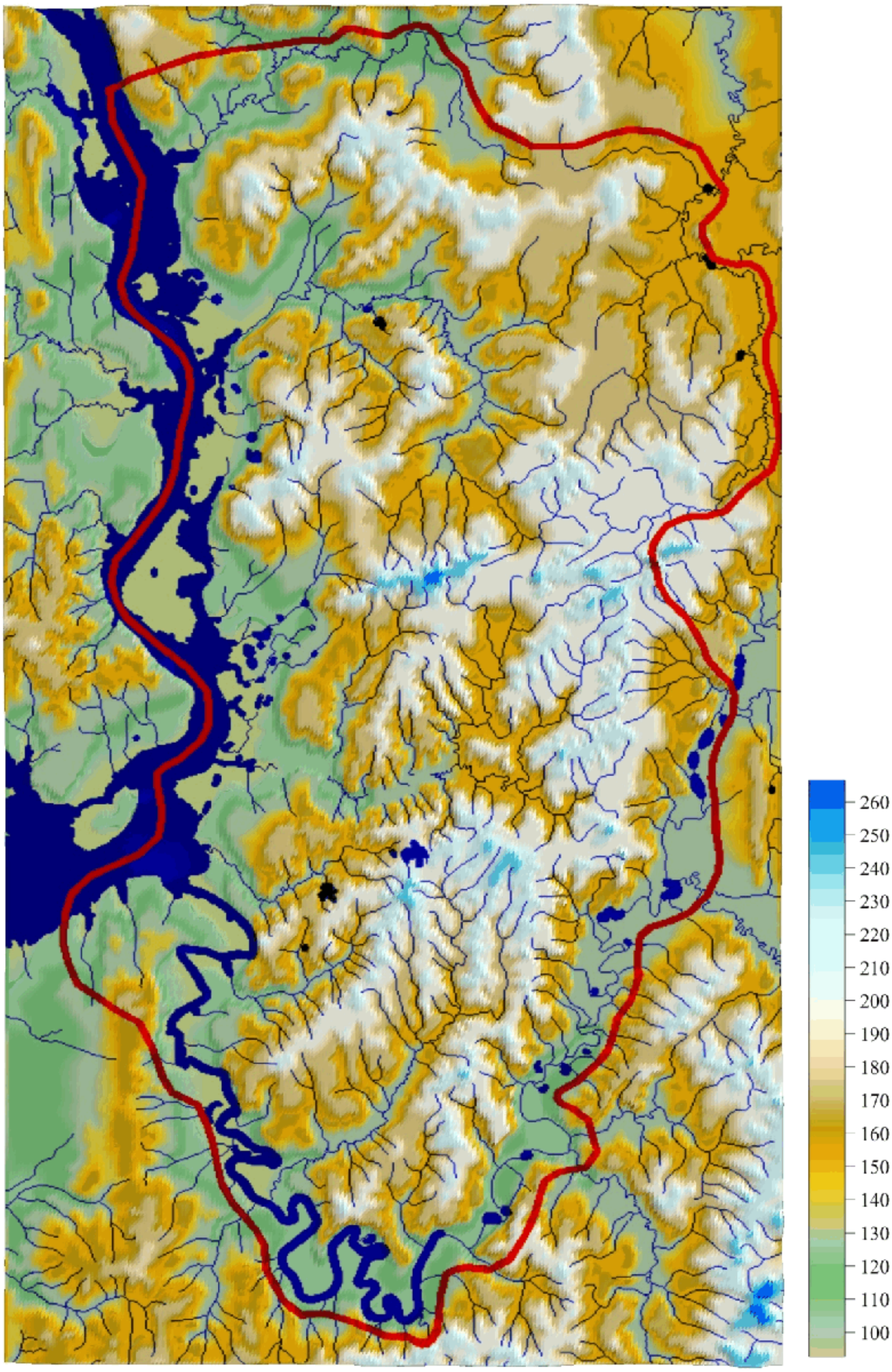


Figure 3.2. Relief of the study area

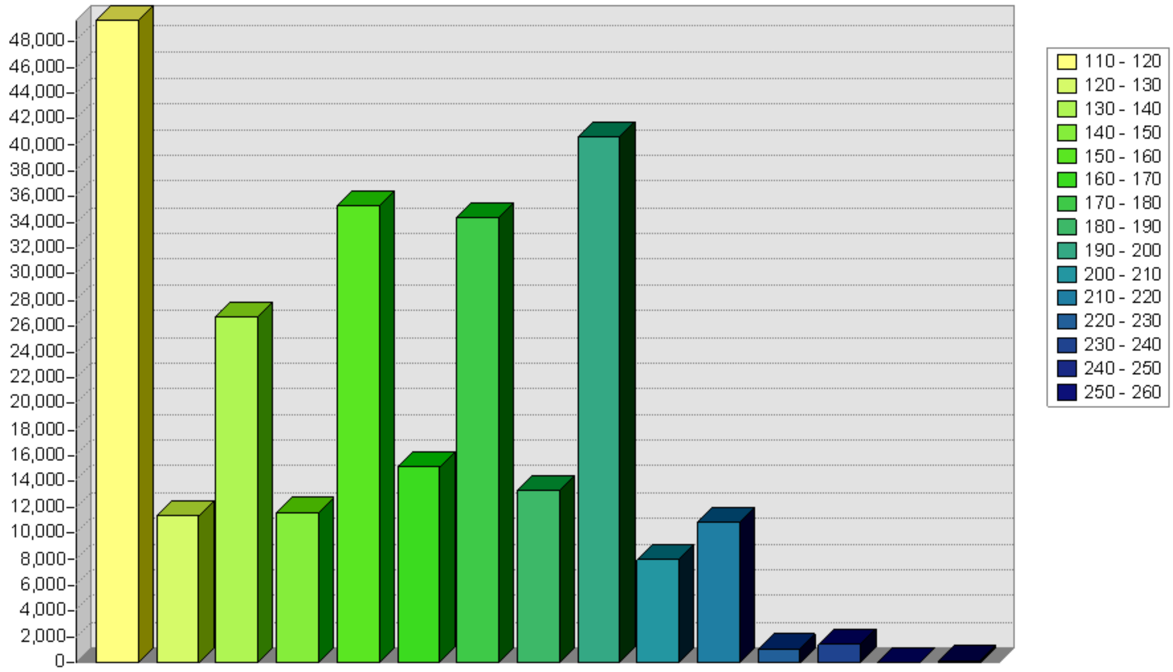


Figure 3.3. Histogram of relief altitudinal distribution

Karstic forms. The manifestation and development of karstic processes is predetermined by the presence of Lower Permian and Upper Permian rocks in the geological structure. This has resulted in the occurrence on the territory of two types of karst: a) carbonate karst developed in the Upper Permian carbonate rocks; б) salt karst connected with the halogen rocks of the Lower Permian Kungurian stage.

The carbonate karst. Its development is caused by the presence of the karstic rocks of the Solikamsk suite of the Upper Permian. A favorable factor for the development of karst in the Solikamsk suite is the extensive presence of fractured systems of different direction and genesis that form a complicated drawing in the permeability zones of karstic massifs.

The surface forms of carbonate karst are presented by single sinkholes (probably, of karst-suffosion nature) which are generally notable for their small sizes, from 2 to 8 m in diameter and up to 3,5 m in depth. Their slopes are grass covered and also partially covered by brush and woody plants, which indicates their slow and passive development. The density of carbonate karst forms reaches 1 sinkholes/sq. km (Nazarov, 1985).

The manifestations of deep carbonate karst are fixed by numerous cases of falls of drilling tools into karstic cavities and loss of drill fluid, as well as by the caliper measurement data (Lapteva, 1974).

3.2. Climatic Conditions

The climate first of all defines by meteorological conditions that affect the regime of groundwaters and more deeply lying confined waters.

The situation of the investigated territory in the center of the continent defines the sharply continental nature of its climate which is expressed in large variations of air temperature both within a year and during a day. To characterize the air temperature, the data from the meteorological station of Berezniki for the period from 1990 to 1993 were taken (Tab. 3.1). The data of long-term mean monthly and the long-term mean annual temperature are presented for period from 1964 to 1988.

The passing of average daily temperature through 0°C to the negative values is observed in the second and the third decades of October, that usually close to the dates of the first snow appearance. The formation of stable snow and ice cover usually coincide with passing of temperature through -5°C in the first decade of November. Winter continues 5,5-6,0 months.

Table 3.1. The data of air temperature by meteorological station of Berezniki

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1993												
-9,4	-13,2	-7,2	2,3	8,9	17,1	18,6	14,8	4,9	0,5	-12,8	-9,8	+1,2
1992												
-16,2	-11,4	-3,5	-0,3	8,4	12,7	16	12,9	11,5	-0,8	-7,8	-8,8	+*1,0*
1991												
-16,1	-11,4	-8,7	6,6	14,9	20,4	17,3	12,9	8,8	5,3	-3,9	-14,6	+2,6
1990												
-14,4	- 5,5	-2,6	4,2	6,9	16,3	18,8	16,1	7,4	-0,8	-7,5	-8,9	+2,5
long-term mean annual (1964-1988)												
-16,3	-14,3	-5,5	1,7	9,1	14,8	17,5	14,4	8,5	0,4	-6,6	-12,4	+1
-14	-13	-6,7	0,4	8,9	15,6	17,7	13,8	8,0	0,8	-8,9	-13,2	0,9

Effect of temperature on the change of groundwater level in the annual cycle is indirect. The main meteorological factors determining the annual variation of groundwater levels are precipitations and evaporation, therefore their annual and long-term annual variability determines variance of surface and groundwater flow. The mean monthly precipitations (mm) for 1990-93 years, according to the meteorological station of Berezniki, and the mean long-term annual data for the period of 1983-94 years are presented in Table 3.2.

Table 3.2. Mean monthly precipitations (mm) from meteorological station of Berezniki

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Mean annual
1990												
47,8	30,8	56,0	25,9	115,8	103,6	53,5	53,2	101,4	*89,6*	53,9	45,2	64,7
1991												
58,6	24,5	37,2	30,3	33,9	61,4	118,7	108,1	90,2	46,1	61,1	43,6	59,5
1992												
55,4	31,8	42,5	78,8	11,6	31,6	66,9	108,6	12,7	147,8	62,8	41,2	57,6
1993												
42,6	31,6	17,9	33,2	85,1	88,7	75,7	69,6	117,9	76,5	12,4	41,0	57,7
long-term mean annual (1983-1994)												
38,8	23,7	23,7	43,1	51,5	75,3	**88,0**	92,5	85,1	72,2	46,0	40,5	56,7

It is worth noting that the warm season with most atmospheric precipitations plays the greatest role in the formation of the annual amounts of atmospheric precipitations (75%, according to the long-term mean annual data).

In some years, both the minimum and the maximum of annual precipitations can be moved to other months. For example, in 1990, the maximum of precipitations was observed in May, in 1991 – in July, in 1992 – in October, in 1993 – in September.

Comparison statistical characteristic of the mean annul and seasonal values of precipitations, according to the meteorological station of Berezniki, are given in Table 3.3.

Table 3.3. Statistical characteristics of annual and seasonal precipitation values from meteorological station of Berezniki

Year	X year	% of rate	X IV-VIII	%	X IX-X	%	X XI-III	%
1993	729,8	107,3	**352,3**	100,5	194,4	123,6	183,1	106
1992	682,3	100,3	297,5	84,9	160,5	**102,0**	224,3	129,9
1991	724,0	106,4	352,4	100,5	**136,3**	**86,6**	235,3	136,2
1990	792,0	116,4	352,0	100,4	191,0	121,4	249,0	173,1
Mean long-term annual	680,0	*100%*	350,0	*100%*	157,3	*100%*	172,7	*100%*

The annual amounts of precipitations of various probability are presented in Table 3.4. Based on it, we can tell that the long-term mean annual amount of precipitations is equal to 680,0 mm – 88% of probability, the annual amounts of precipitations for 1990-1993 respectively are equal to 64%; 80,5%; 87,5%; 79 % of probability.

Table 3.4. Annual amounts of precipitations with various probability (mm)

Station	Probability (%)										
	5	10	20	30	40	50	60	70	80	90	95
Solikamsk	954	906	853	813	780	748	720	687	644	580	525
Berezniki	1040	998	944	902	869	835	807	773	726	669	600

Solid precipitations make up 25% of the total precipitation. The dates of appearance and disappearance of snow cover, and formation and destruction of the stable snow cover given in Table 3.5, according to data of the meteorological station of Berezniki.

Table 3.5. The dates of appearance and disappearance of snow cover,

and formation and destruction of the stable snow cover

The number of days with snow cover	Data of appearance of snow cover			Data of formation of snow cover			Data of destruction of snow cover			Data of disappearance of snow cover		
	average	early	late	average	early	late	average	early	late	average	early	late
171	17/X	16/IX	14/XI	1/XI	1/X	-	13/1V	-	30/1V	23/IV	29/III	10/VI

Table 3.6. The average decade height (cm) of the snow cover for the period from 1989 to 1993, according to the meteorological station of Berezniki

X			XI			XII			I			II			III			IV			V		
1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
0	6	9	10	16	27	42	48	58	77	91	99	103	85	105	104	107	106	97	62	24	7	0	1

The maximum height of the snow cover falls on the beginning of snowmelt (100-107 cm).

The reserves of water in the snow cover define, to a large degree, the size of spring flood, the provision of soil moisture and the maximum levels of groundwater in the spring period. The average values of water reserves in the snow cover among the largest in the winter, according to the meteorological stations of Solikamsk and Berezniki, are respectively equal to 191 mm and 174 mm (Handbook on the Climate of the USSR, 1968).

Table 3.7. Reserves of water in the snow cover according to the snow surveys on the last day of decade (mm)

X			XI			XII			I			II			III			IV			average of the largest in winter
1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
Solikamsk (feild)																					
	*	*	19	32	40	58	70	93	111	125	123	136	147	156	167	171	172	117	58	*	191
Berezniki (field)																					
	*	*	8	26	34	54	67	84	106	111	130	137	141	159	158	170	144	78	*26*	*	174

(*) – means that the number of days with this type of precipitations is ≤0,5.

There are no direct observations related to the evaporations on the studied area.

The mean long-term annual value of annual layer of total evaporation is equal to 420-440 mm (Resources of surface waters of the USSR, 1978). In winter (XII-III), the average evaporation is equal to 20-25 mm, and it is changed within the limits from 90 to 120 mm in spring. In the summer period (VII-IX), more moisture is evaporated than comes on the surface of catchment areas thanks to the previously accumulated reserves of moisture. The total value of evaporation for this season varies from 230 to 270 mm. In autumn (X-XI), the evaporation is equal to 60-70 mm.

The annual distribution of evaporation for seasons is distinguished by a higher consistency (Table 3.8).

Table 3.8. The mean long-term annual seasonal variations of evaporation

Territory	Winter (XII-III)	Spring (IV-VI)	Summer (VII-IX)	Autumn (X-XI)
Predural'ye (forest zone)	5,9	26,2	59,0	8,9

3.3. Hydrography

The river network of the studied territory belongs to the basin of the river of Kama which is the main water artery (the water storage of Kama). The biggest of left tributaries are Borovaya, Usolka, Lenva, Yayva.

The main hydrographical characteristics of the rivers in the region are taken from (Resources of surface waters of the USSR, Middle Ural and Priuralie 1973) (App. 1).

According to the scheme of hydrological zoning, the area under research belongs to the first region. The runoff coefficient is equal to 0,50-0,70 and indicates that the conditions of runoff are favorable, i.e. up to 70% of precipitations flow to the rivers. Coefficient of within-year intra-flow regulation (φ) equal to *0,55-0,6* shows a relatively even distribution of river runoff during a year - a share of stable (basic) runoff exceeds 50% of its annual volume.

One of the main indicators of development of the hydrographical network is the drainage network density coefficient which is equal to 0,51-0,6 km/km^2 that means quite developed river network.

Good drainage conditions of the territory resulted in the almost complete absence of lakes (App.1).

The main flow direction of most rivers is latitudinal. The rivers of the Kama basin have a typical view for plain rivers. The flow velocity of the rivers is insignificant. The widespread easily soluble rocks on the plain cause the unstability of riverbeds in the plan and development of free meanders. The main type of riverbeds is the free meandering (the rivers of Borovaya, Usolka).

The rivers of the studied territory belong to the type of rivers with a clearly defined spring flooding, summer-autumn rainfall flooding and long-term and consistent winter low-water level. Snow waters have predominant value in river recharge. The share of snowmelt waters in the total rivers runoff reaches 75%.

On the average, approximately 25% of the annual runoff is formed by subterranean way (Table 3.9) (Baldin V.A. et al, 1998).

It is worth noting that the rivers of Borovitsa and Usolka differ from the other rivers of the regions by elevated contribution of groundwater in their recharge (40-45% of the annual runoff) which is also confirmed by the presence of numerous springs (Popovtsev, 1986 f; Moshkovskiy).

The ratio of groundwater and surface water runoff varies significantly with seasons.

In spring the contribution of groundwater runoff is not large, on the average, it is equal to 10-15% of the cumulative runoff for a season. In the surface water runoff, almost an exclusive role belongs to snow melt waters since in the period of spring flooding an amount of rainfalls is insignificant (Resources of surface waters of the USSR, Middle Ural and Priuralie 1973).

The cumulative runoff, in the summer-autumn low water period on a large part of the territory, is formed on 50-60% from the surface and on 40-50% from the groundwater runoff.

In winter the rivers are fed by groundwater storage.

Table 3.9. Division of runoff hydrographs into surface and subterranean components, and according to sources of rivers recharge.

Surface and subterranean components of runoff in different seasons and for a year (in% from a seasonal and annual runoff)												Estimated ratio of separate sources of rivers recharge	
Spring flooding				Summer-autumn season			Winter		A year				
Surface runoff		Groundwater runoff	Percentage of seasonal runoff in the annual (%)	Surface runoff (rain waters)	Groundwater runoff	Percentage of seasonal runoff in the annual (%)	Groundwater runoff	Percentage of seasonal runoff in the annual (%)	surface runoff		Groundwater runoff	Percentage runoff (in%) relative to the annual	
Snowmelt waters	Rain waters								Snowmelt waters	Rain waters		snowmelt waters	rain waters
82	**4**	*14*	**65**	**55**	*45*	**25**	**100**	**10**	**56**	**20**	**24**	75	**25**

The particularities of runoff seasonal distribution are defined by conditions of rivers recharge (Fig.3.4, 3.5).

Nearly 60% of the annual runoff occurs in the period of spring flooding. Redistribution of runoff volumes within a year occurs depending on the water content of a year.

In years with very small amounts of water (low-water years), the share of spring flooding increases up to 65%, and years with very large amounts of water (high-water years) are characterized by higher runoff in the summer-autumn low water period. – 41%. The runoff in a winter low water period is stable and equal to 7% (Table 3.9).

The spring flooding usually begins in the second half of April. The amplitude of variations of dates, when spring water begins to rise, in different years, is relatively slight – a month on the average.

The latest dates of beginning of flooding period fall on the first two decades of May. The early dates fall on the first decade.

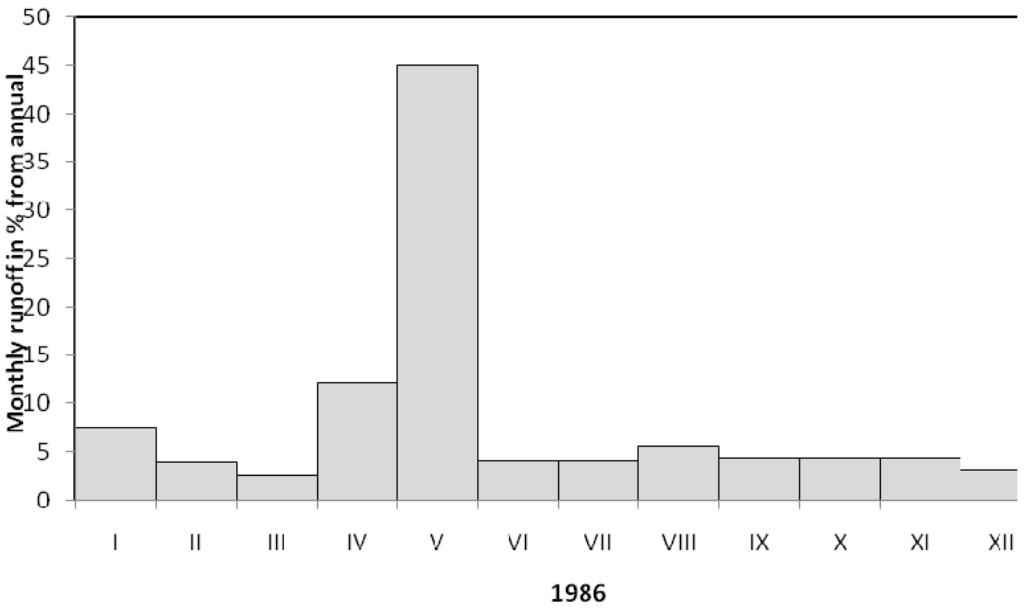
The flooding period lasts for 30-70 days.

On rivers of the region, the seasonal flooding often has a multi-peak form due to both the interrupted character of snow melting and the rising of rain waters overlaying the snowmelt runoff.

In the summer-autumn period, the stable water level is often interrupted by rain floodings which, in some rare years, are commensurable with spring flooding in volume of maximum discharge. On the average, there are 1-3 floodings in the rivers.

The winter low-water period is distinguished by stability, long duration and low runoff. This period continues 140-160 days, on the average.

a)



b)

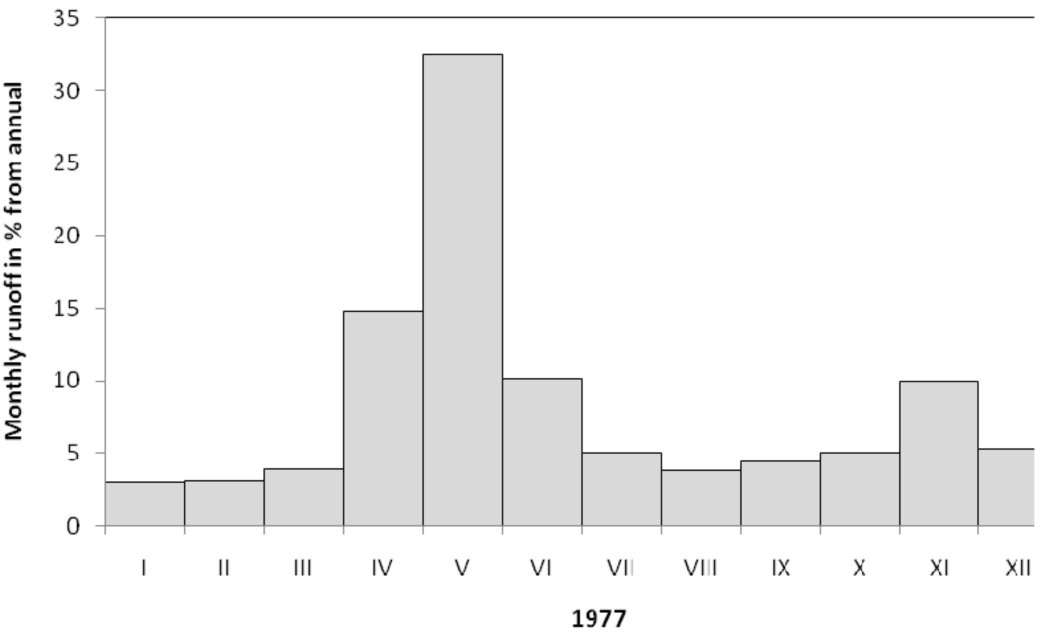
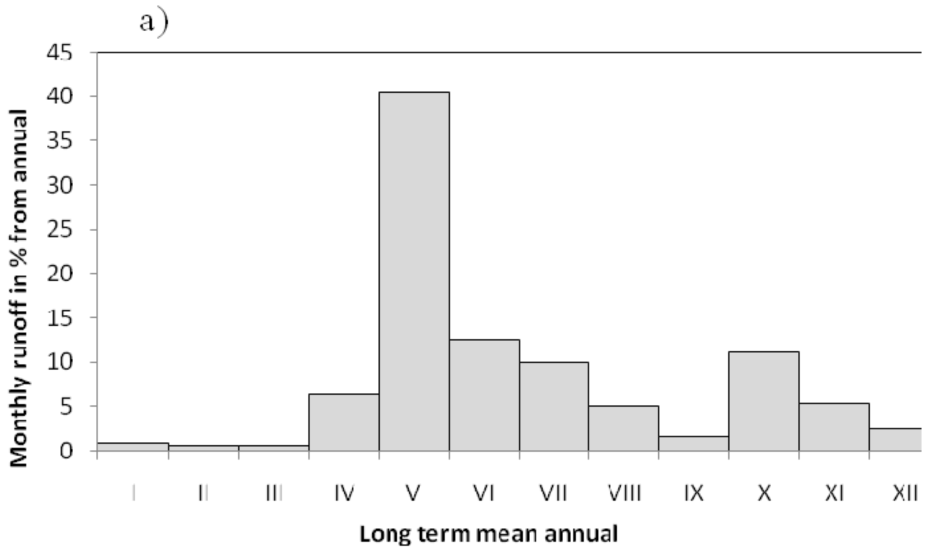


Figure 3.4. Annual runoff distribution. a) r. Usolka (village Horyushino); b) r. Borovaya (Borovitsa)



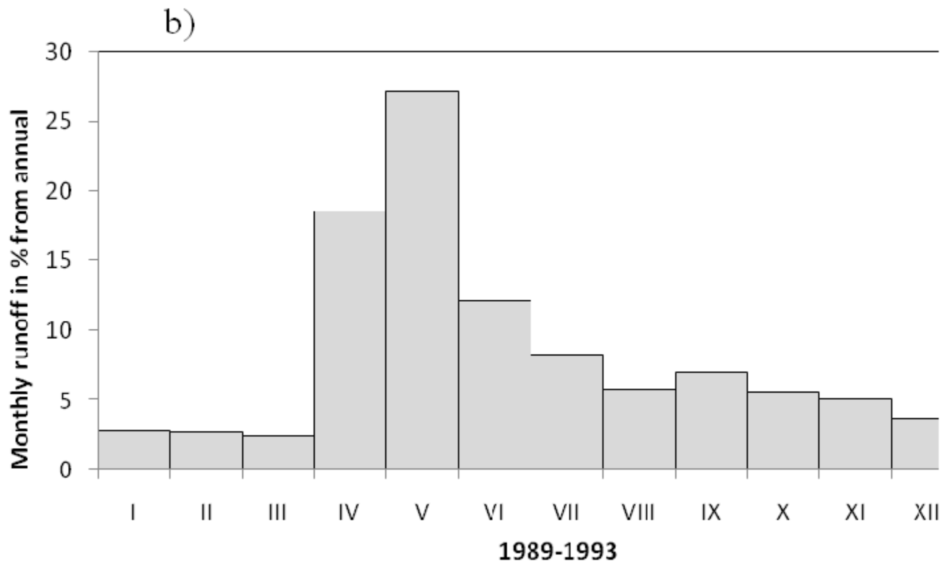


Figure 3.5. Annual runoff distribution. a) r. Yaiva – (town Baza), b) r. Bygel

Today, there are no stationary hydrological posts on the studied area. The episodic runoff monitoring has been carried out on rivers of Borovitsa, Usolka, Sylva, Potva, therefore all calculating relation were obtained with the use of materials for similar rivers. The most close corelation of water discharge (r = 0,95; r = 0,98) have been observed on the posts of the river of Kolva – the village of Petretsova and Yayva – the village of Baza.

To calculate the average annual amounts of water discharge, r. Yaiva was accepted as a river-analogue which has the highest correlation coefficient (r = 0,98).

The module of runoff (runoff in liter per second per square kilometer) of low-water summer period of 90% probability for river section line was calculated according to the formula:

$$M_{90\%\,i} = Q_{90\%\,i} \cdot F,$$

Where: $Q_{90\%\,i}$ – discharge of *90%* probability in a section line; F – area of a catchment basin.

The results obtained from calculations (App. 2, Baldin et al, 1998) are need to be considered as relatively representative, since one-time measurements of discharges 1990-91 fall on period of rain floodings, in connection with it the share of surface water runoff increase up to 35-50%, and it is difficult to perform the matching of different basins of flood waves according to synchronism.

Due to the fact that there weren't any winter measurements on the water streams, for transformation of the module of runoff of 90% probability for the summer low-water period to the some module for winter period, there was used a ratio between the modules of summer and winter runoff of the analogue river (Km) Yayva (village of Baza).

$$K_M = \frac{M_{90\%summ}}{M_{90\%wint}} = \frac{2,3}{1,95} = 1,18$$

Therefore, $M_{90\%wint} = M_{90\%summ}/K_M$

The results are presented in App. 2 (Baldin et al, 1998).

The analysis of modules of runoff of 90% probability in the winter low-water period (Baldin et al, 1998) allows to approximately allocate the areas with maximum increase of river runoff for account of groundwater discharge and divide them into several groups:

I. An area that unites the right tributaries of the Usolka river (Rostovitsa, Bubrov, Permyanka, Berezovka, the right tributary of Berezovka), that confirmed by presence of the groundwater deposit "Usolsky". The module of runoff is more than 4 $l/s{\cdot}km^2$.

II. The area units the right tributaries of the Borovaya river (the Korel river, the Korel stream, Berezovka, an unnamed stream of Borovaya), here there is the groundwater deposit "Borovitsa". The module of runoff is more than 4 $l/s{\cdot}km^2$.

III. The area of the Sylva river. It is possible to judge the water abundance in this area by the ascending springs with a high debit, and here there was allocated a water-abundant fissured zone (Melekhov, 1975. The module of runoff is more than 4 $l/s{\cdot}km^2$.

IV. The area includes the tributaries of the Izver river (the rivers of Legchim and Orlovka), here where were discovered the Izverskoe and Legchimskoe deposits of groundwater. The module of runoff is equal to 3,5-4.5 $l/s{\cdot}km^2$.

V. The area with the river of Unva and its tributaries. The module of runoff is equal to 2,5-5.5 $l/s{\cdot}km^2$.

All the above-mentioned water-abundant areas are the places of groundwater discharge of the Upper Solikamsk water-bearing stratum.

VI. The area includes the river of Volim and an unnamed tributary of r. Volim, here there is the operating water intake "Volimskiy". The module of runoff is equal to 2,7-5.7 $l/s{\cdot}km^2$.

VII area including the river of Lenva and Telepaevka. The module of runoff is equal to 2,7-6.5 l/s·km^2.

VI and VII water-abundant areas are connected with groundwater discharge of Sheshminski deposits. Particulary on this area the Sheshminskiy water-bearing complex is characterized by high conductivity and water transmissibility.

3.4. Soils

According to the soil map of the Perm region (1989), in the investigated territory are extended alluvial, sod-medium podzolic, sod-strongly podzolic, strongly podzolic and medium podzolic soils, also soils of gullies, ravines, flood plains of small rivers and adjoining slopes (Figure 3.6). The most widespread are of strongly podzolic and sod-strongly podzolic types of soils (Figure 3.7). Prevailing soil mechanical composition is given in table 3.10.

Table 3.10. Types of soil and the prevailing mechanical composition

Types of soil	Prevailing mechanical composition
Alluvial	Heavy loam
Sod-medium podzolic	Heavy loam
Sod-strongly podzolic	Heavy loam
Strongly podzolic	Medium loam
Soils of gullies, ravines, flood plains of small rivers and adjoining slopes	Loamy and sandy loam deposits
Medium podzolic	Sandy loam

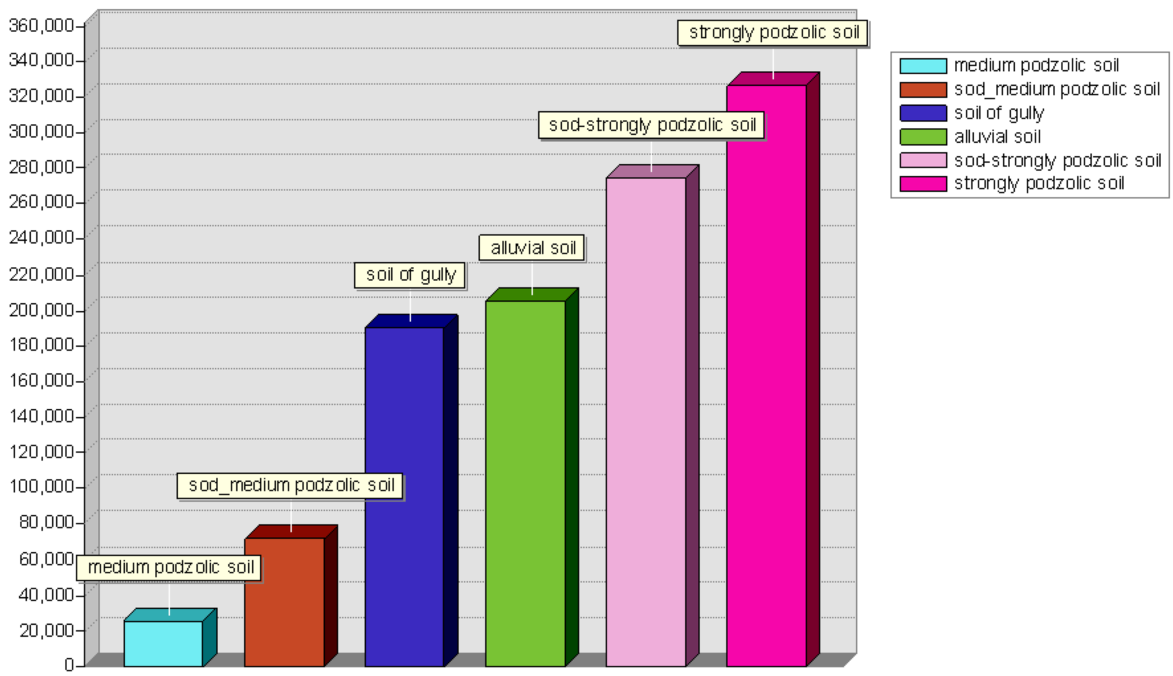


Figure 3.7. Distribution of soil types

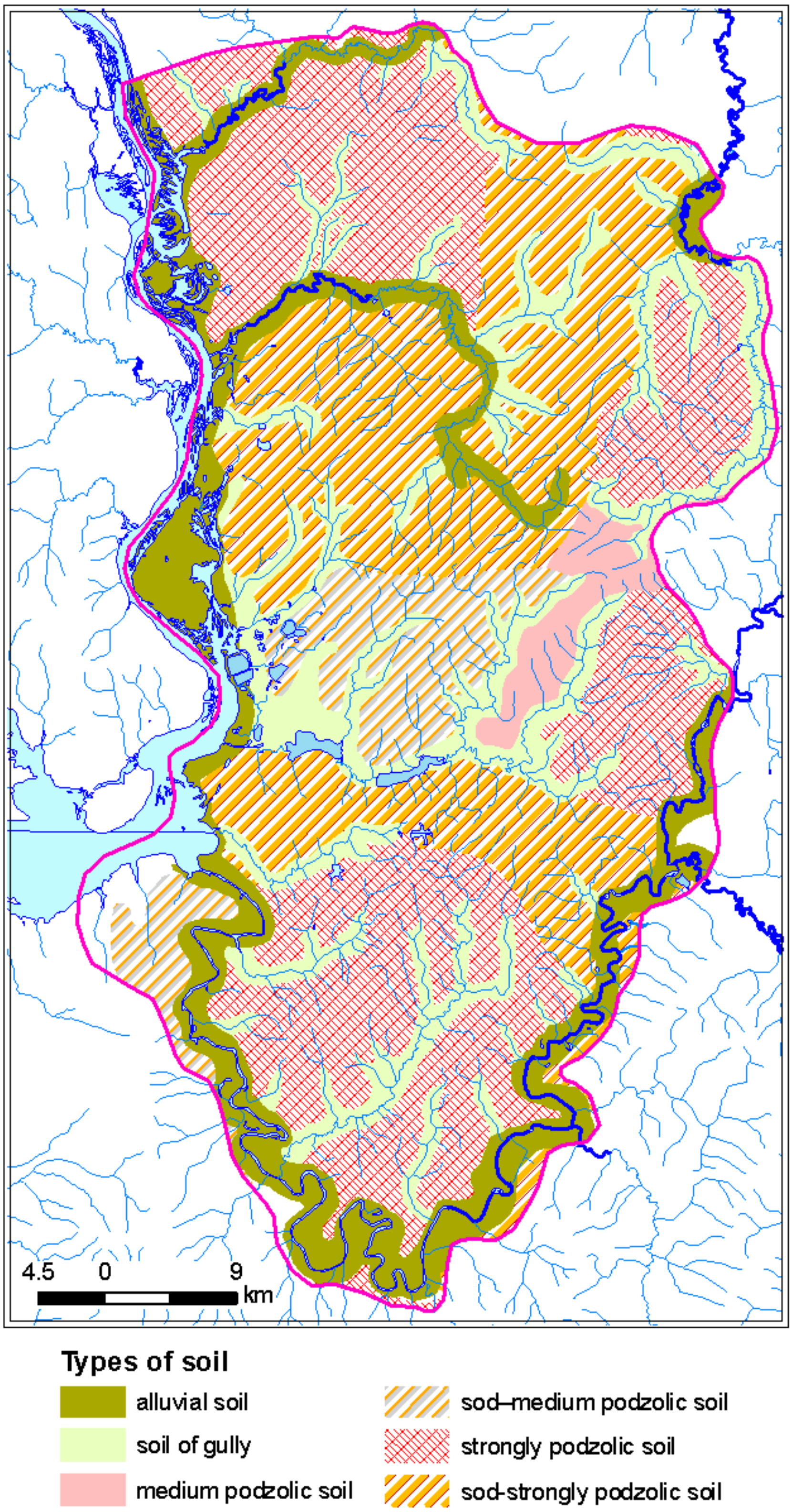


Fig. 3.6. Soil map (Soil map of the Perm region. Scale 1:700000. Signaevsky, 1989)

3.5. Geological structure

The territory of the deposit is composed by the Upper Permian deposits overlaid by a cover of Cenozoic formations with an average thickness of 5-15 m. The general stratigraphical scheme is presented on Fig. 3.8. More ancient deposits do not come up to the surface and were opened up by a key well (well 1-OP, depth 2973 m) and oil exploration wells many of which have passed through the deposits of the Paleozoic and were stopped in the rocks of the Vendian complex. Besides on the territory there are some oil deposits, lying under the salt deposits (Figure 3.1, 3.9). According to the geophysical data, a crystal basement is located at depths between 4-5 km with general tendency to immersion toward the east.

Further, there are presented full descriptions of stratigraphical divisions from the ancient ones to the recent ones. For this describing the materials of research of this territory have been used, as well as the data from wells of the Solikamsk GRP and the association “Permneft”.

The Kungurian stage is represented by two horizons – the Filippovskiy and the Irenskiy, that deposits are widely spread throughout the whole territory of the Solikamsk depression.

The Filippovskiy bedrock, on most part of the Solikamsk depression, is represented by the ***Karnaukhovskaya suite*** (P_1*kr) composed* of four alternating units of sulphate and carbonate rocks. The total thickness of the suite is approximately equal to 100 m.

The deposit proper is represented by salts of halogenous formation of the Solikamsk depression which includes the deposits of the Karnaukhovskaya, Bereznikovskaya suites and the Lower Solikamsk subsuite (Ivanov, Voronova, 1975) (Figure 3.10).

The Bereznikovskaya suite is composed of an argillaceous-anhydrite and salt strata.

The argilliferous-anhydrite strata (P_1br_1), which A.A. Ivanov called as argillaceous-carbonate sulphates-saliferous formation (Ivanov, Voronova, 1975) and V.I. Kopnin (1995) – as argillaceous-dolomitic-anhydrite substrata, is composed by marl, argillite, dolomite and, to a lesser degree, limestone, anhydrite, rock salt, siltstone and sandstone. The thickness of this formation varies from 145 m (on the west of the depression) to 325 m (on the east) (Ivanov, Voronova, 1975), being equal to 230 m, on the average.

The salt strata with the total thickness of up to 550 m is subdivided (bottom-up) into underlying rock salt (URS – P_1br_2), the potash deposite (P_1br_3) composed of sylvinite zone (SZ) and carnallite zone (CZ), and covering rock salt (BRS – P_1br_4) (See Fig. 3.10)

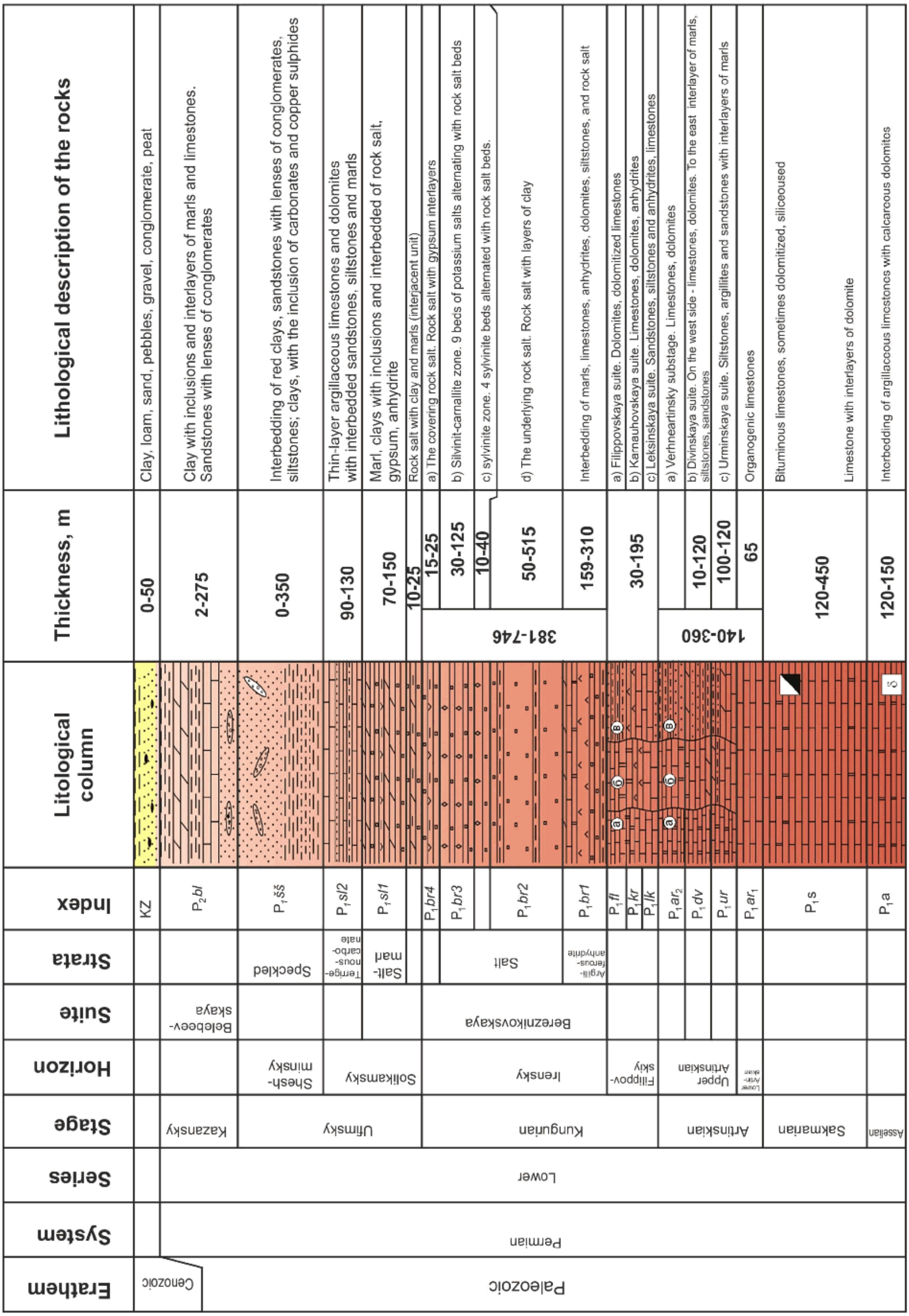


Fig. 3.8. Stratigraphical scheme of the Permian deposits of the Upper Kama potassium salt deposit (according to A.I. Petrik)

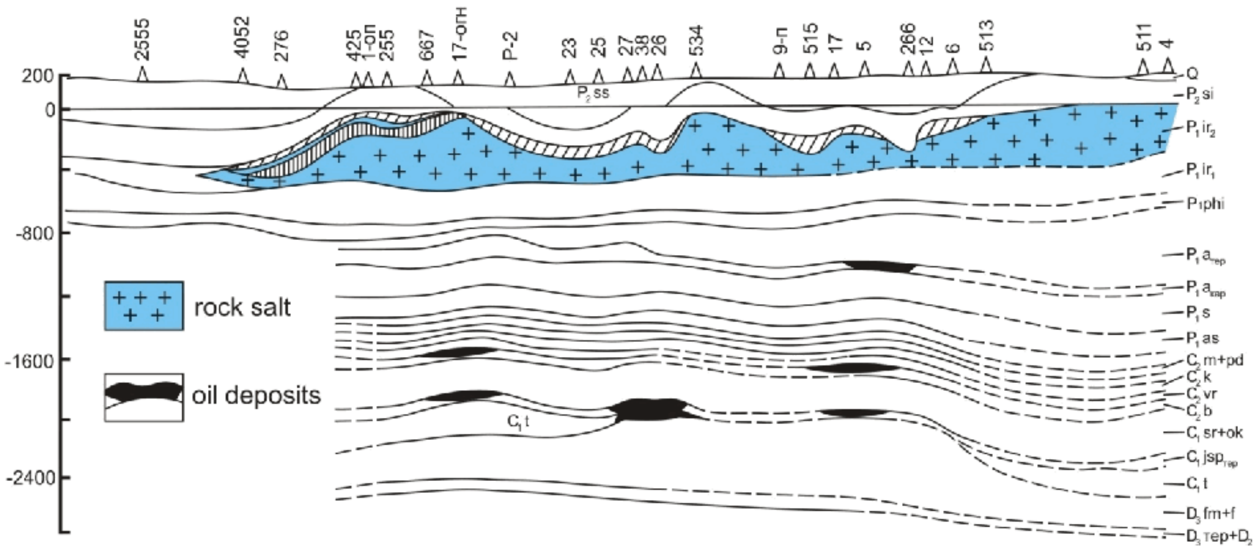


Fig. 3.9. Geological cross-section through Durinsky depression (by A.Zyev, 1982)

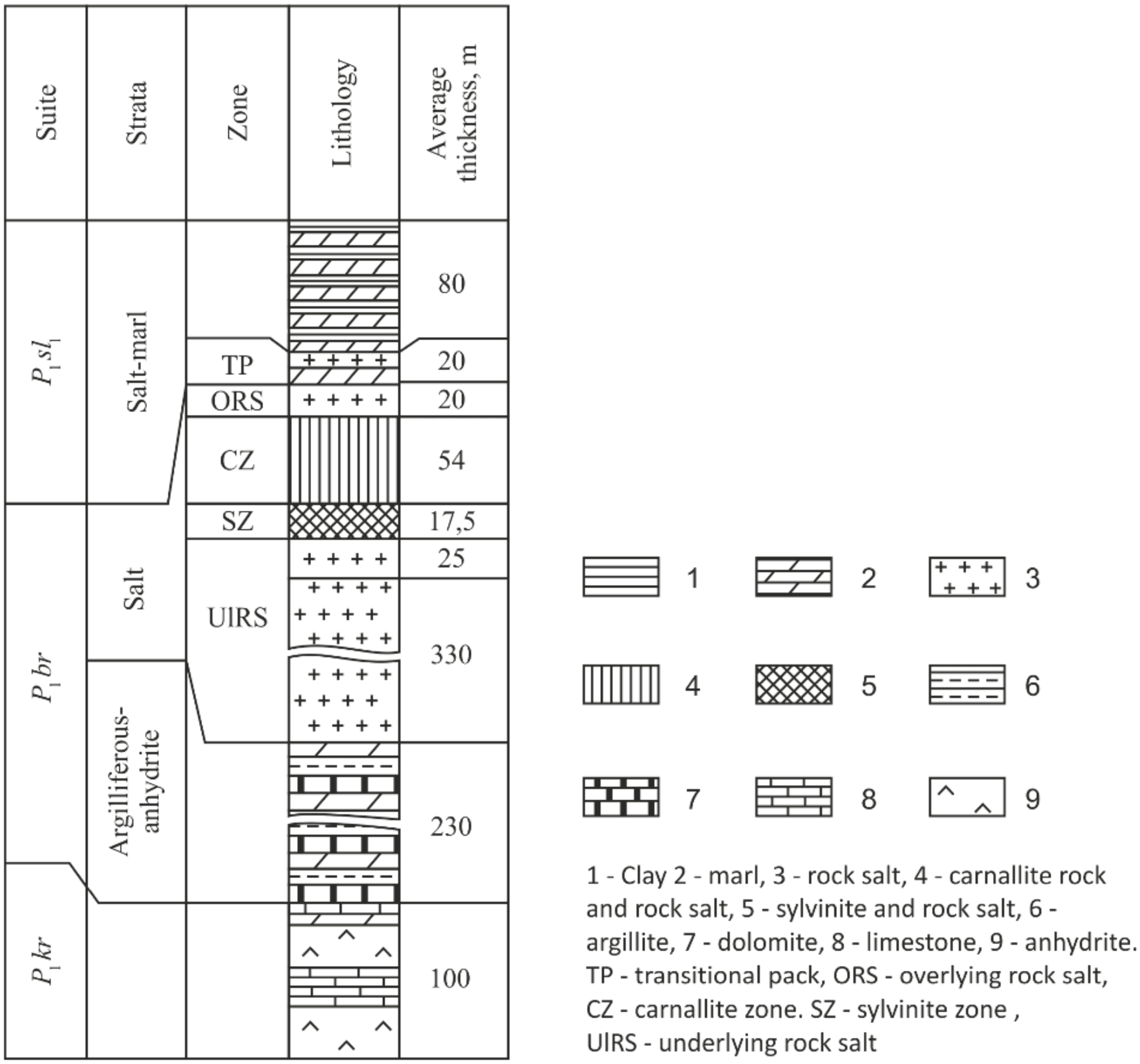


Fig. 3.10. Stratigraphic section of the halogen formation of Solikamsk depression

(Kudryashov, 2001)

The potash deposit of the Upper Kama deposit is represented by a series of productive formations divided with rock salt. According to its composition, the deposit is divided into a sylvinite zone and a carnallite zone.

The sylvinite zone is composed of stratums of red and striated sylvinite separated by stratums of rock salt. The thickness of the sylvinite zone varies from 3,3 to 30,0 m, and is equal to 17,4 m, on the average.

The carnallite zone is composed of alternating stratums of potassium-magnesium salts and rock salt. The thickness of the carnallite zone varies from 38 to 80 m (being 53,8 m, on the average).

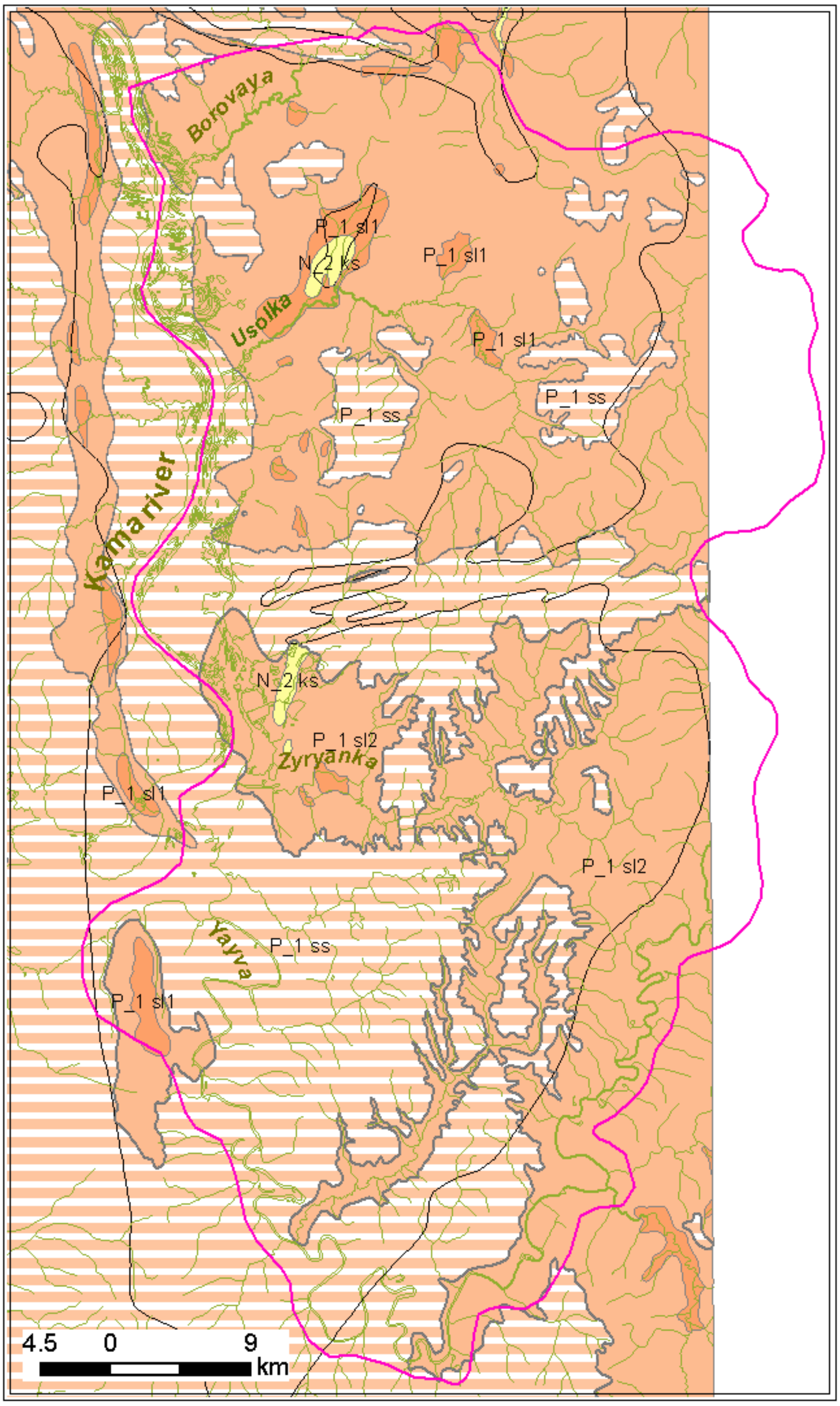
The covering rock salt (CRS) is spread on the predominant part of the deposit area, but absents on the crests of some raisings. The thickness of the CRS slightly varies (16-22 m) and is equal to 20 m, on the average.

The Ufimian stage is represented by the Solikamsk and the Sheshinskiy horizons (see Fig. 3.11).

The Lower Solikamsk subsuite (P_1sl_1), represented by salt-marl strata (SMS) in halogenous formation, is spread throughout the whole area of the deposit. The lower part of SMS containing stratums of rock salt is called an transitional unit (TA). The roof of the TA coincides with the first upper stratum of rock salt, i.e. it is not a stratigraphic level, as it is the salt table. The thickness of the TA reaches 88 m, being equal to 20 m, on the average. The total thickness of the SMS varies from 15 to 160 m and is equal to nearly 100 m, on the average.

The Upper Solikamsk subsuite that lied above the halogenous formation is represented by a terrigenous-carbonate strata (TCS – P_1sl_2). The TCS is subdivided into two lithologic zones: the lower one – marl-dolomite-limestone and the upper one – limestone-terrigenous (V.I. Kopnin, 1995). The lower zone with an average thickness of 65-70 m is composed of limestones, dolomites and thinly laminated marls. The limestone-terrigenous lithologic zone with thickness of 52-64 m is represented by claystones, siltstones, very fine sandstones and limestones. The total thickness of the TCS varies from 90 to 170 m.

The Sheshminskaya suite ($P_1\check{s}\check{s}$) is represented by a speckled strata (SS). The strata is composed of sandstones and brown, greenish-grey and grey siltstones, occasionally, with thin interlayers of marls and limestones. Sandstones and siltstones calcareous, crossbedded, quite often with some cupriferous compounds in the form of malachites and azurites (cupriferous sandstones). Gypsum is presented in the form of lenticular interlayers, concordant and cross



——	Boundary of the potash deposits
N2 ks	Neogene. Pliocene. Kostanay suite. Sand, gravel-pebble deposits with interlayers of clays
P1 ss	Permian system. Upper series. Ufimsky stage. Sheshminskaya suite. Rhythmic interbedding of argillites, siltstones with interlayers of sandstones and conglomerate lenses.
P1 sl2	Permian system. Upper series. Ufimsky stage. Solikamskaya suite. Terrigenous-carbonate stratum. Interbedding of limestones, marls with clay, interlayer of siltstone, rarely sandstones.
P1 sl1	Permian system. Upper series. Ufimsky stage. Solikamskaya suite. Salt-marl stratum. Interbedding of dark-gray marls and clays with pyrite and gypsum inclusions, in the lower part - interlayering of gypsum and rock salt.

Fig. 3.11. Geological map of the Solikamsk depression (fragment)

(Haritonov et al., 2002)

streaks. Within the Upper Kama salt deposi, the thickness of Sheshminskiy horizon varies from 0 to 675 m.

The Kazanian stage **(P_2kz)**. Deposits of this stage are spread to the west of the salt deposit (the right bank of the Kama river) and are represented by a formation of sandstones and siltstones, with lenses of conglomerate, interlayers of clays, limestones and marlstones.

The Cenozoic deposits are fragmentarily developed on the deposit area. Thus, A.A. Ivanov (1975) conditionally refered color clays and quartz sand-gravel-pebbly deposits, uncovered in the northern part of the Durinskaya area, to the Pleogene deposits. These deposits are up to 17,4 m thik. Neogene (Upper Miocene) deposits have been discovered in the overdeepenings of the ancient bed of the river of Prakama. They are represented by clays, sands and clay loams, with interlayers of turf and lignite. The thickness of the Neogene deposit is equal to 20-36 m.

The Quaternary system **(Q)** is represented by unconsolidated formations of different origin (Fig. 3.12): eolian sands (up to 3 m), peat bog deposits (up to 5 m), alluvial sands, clays, pebbles (1,5-30 m), lacustrine-alluvial (up to 25 m) and periglacial (up to 10 m) sand loams, clay loams and clays, fluvioglacial, morainic and other formations (1,5-10 m). In some cases (overdeepening of paleoplains, zone of leaching of salts, etc.), the thickness of quaternary deposits reaches 80 m.

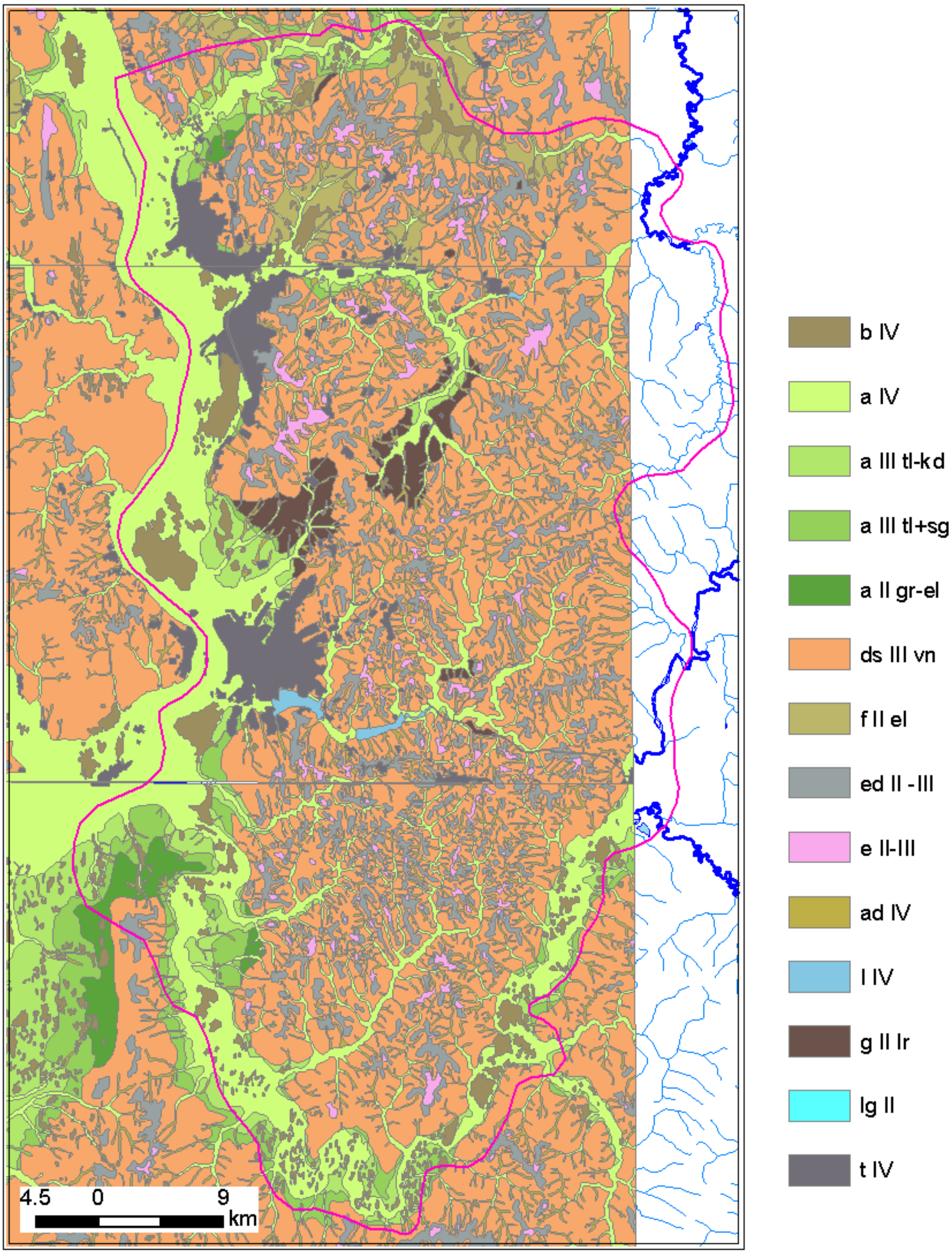
Tectonics and neotectonics

The Pre Ural fore deep is a large synclinal structure transitional from the Russian platform to the folded Ural. The most part of the deep, including the Solikamsk depression, is distinguished by a more profound bedding of the Pre Kungurian deposits than on the platform and in the folded Ural, as well as by development of salts in the Kungurian deposits. The transition from the platform to the deep is gradual, since during formation of the latter in the Early Permian epoch, its migration toward the west occurred with overlapping on the eastern part of the Russian platform. For the boundary between these tectonic areas to the south from River. Kosva and to the south of the Solikamsk depression, there was accepted the steep bench (1-5°) of the crystalline basement surface, accompanied by a gradient zone of the gravimetric field and identified with Krasnoufimsk regional fault. There is no such bench in the Kungurian and the Artinskian deposits, and the western boundary of the Pre Ural fore deep is drawn notionally, taking into account the increase of thickness and the facial variation of the Lower Permian deposits. The eastern boundary of the Pre Ural fore deep (and the Solikamsk depression) is drawn along occurrence of Lower Permian molasses. On geological map this line lies slightly to the west of the front folds of Ural, near surface exposure of the Artinskian stage deposits from under the Kungurian deposits (through the village of Nyrob, the city of Krasnovishersk, the village of Vsevolodo-Vilva, the city of Tchusovoi).

The Solikamsk depression is a meridionally extended structure of approximately 240 km in length and up to 70-75 km in width. From the west, it is confined by the Kolvinskaya saddle which is marked out by exposures of the Artinskian and more ancient deposits among the Kungurian ones. The Kosvinsko-Tchusovsckaia saddle confines the depression and is distinguished with an elevated level of bedding of the Kungurian and the Artinskian deposits.

The neoctectonic processes actively affect the hydrogeological conditions of the region. According to the data of morphometric researches carried out on the described territory in the process of medium-scale hydrogeological survey, modern movements are most clearly exhibited in the relief by density and depth of the erosion pattern stripping. The highest coefficients of erosive roughness correspond to the areas having the most intensive risings at the present time, and the areas of weak ascending movements are characterized by small coefficients. The territory of intensive raises is characterized by higher water-abundance of rocks due to significant tectonic fracturing and intensive filtration of atmospheric precipitations, and the territory of relative depressions is characterized by a weak abundance of water.

The areas with high coefficients of erosive roughness of relief are established on the territory of the Upper Kama depression – in the basins of the rivers of Kosa, Ysolka, Pozhva, on the interfluve of Kama and Obva, and in other regions. Substantial areas with high coefficients of erosive roughness are also observed within the confines of the Solikamsk depression (Melekhov, 1975) and the Permsko-Bashkirsky arch. These areas also contain water-abundant zones and groups of the zones.



b IV - biogenic deposits; a IV - alluvial deposits; a III tl-kd - alluvial deposits of the I fluvial terrace; a III tl+sg - alluvial deposits of the II fluvial terrace; a II gr-el - alluvial deposits of the III fluvial terrace; ds III vn - dealluvial deposits; f II el - fluvioglacial sediments; ed II –III - eluvial-dealluvial deposits ; e II-III - eluvial deposits ; ad IV - alluvial-dealluvial deposits; l IV - lake deposits; g II lr - glacial deposits; lg II – lake-glacial deposits; t IV - technogenic (anthropogenic) deposits

Fig. 3.12. Quaternary deposits map of the Solikamsk depression (fragment)

(Haritonov et al., 2002)

CHAPTER 4

HYDROGEOLOGICAL CONDITIONS

According to the hydrogeological zoning of USSR of scale 1:2500000 (Ostrovsky et al., 1988) the Upper Kama salt deposit belongs to Preduralsky (Pre-Urals) complex basin of stratal water.

Suprasalt complex of rocks occupies the upper hydrogeological floor (Vsevolozhsky, 1983), its lower confine is the roofing of Berezniki suite deposits, acting as regional aquitard, and its upper part is the land surface. Groundwaters of the floor are concentrated in Upper Permian and, partially, in alluvium and Palaeogene-Neogene deposits.

According to the acting scheme of hydrogeological stratification (Ostrovsky et al., 1988) on the territory of research in the suprasalt strata there is allocated the following hydrogeological subdivisions (Ikonnikov E.A., 1990) (see Fig. 4.1):

- Water-bearing, locally poorly productive water-bearing Quaternary alluvial horizon;
- Water permeable, locally water bearing Elovsky fluvioglacial horizon;
- Poorly productive water-bearing, locally water bearing Sheshminsky terrigenous complex;
- Water-bearing Upper-Solikamskaya terrigenous-carbonate subsuite.

The water-bearing Upper-Solikamskaya terrigenous-carbonate subsuite and the poorly productive water-bearing, locally water bearing Sheshminsky terrigenous complex are the main hydrogeological subdivisions in witch practically all groundwaters of suprasalt strara are concentrated.

4.1. Hydrogeological structure

Water-bearing, locally poorly productive water-bearing Quaternary alluvial horizon – aQ

The horizon is spread in the river's valleys: Kama, Yayva, Borovaya, Usolka, Zyryanka, etc. It unites waters of modern, upper, middle and lower stages of the Quaternary system. The horizon is considered as united hydrogeologial subdivision due to its position in relief, identical geological structure, unified gradation of permeability and transmissivity values.

Thickness of the alluvial deposits is given in the Table 4.1.

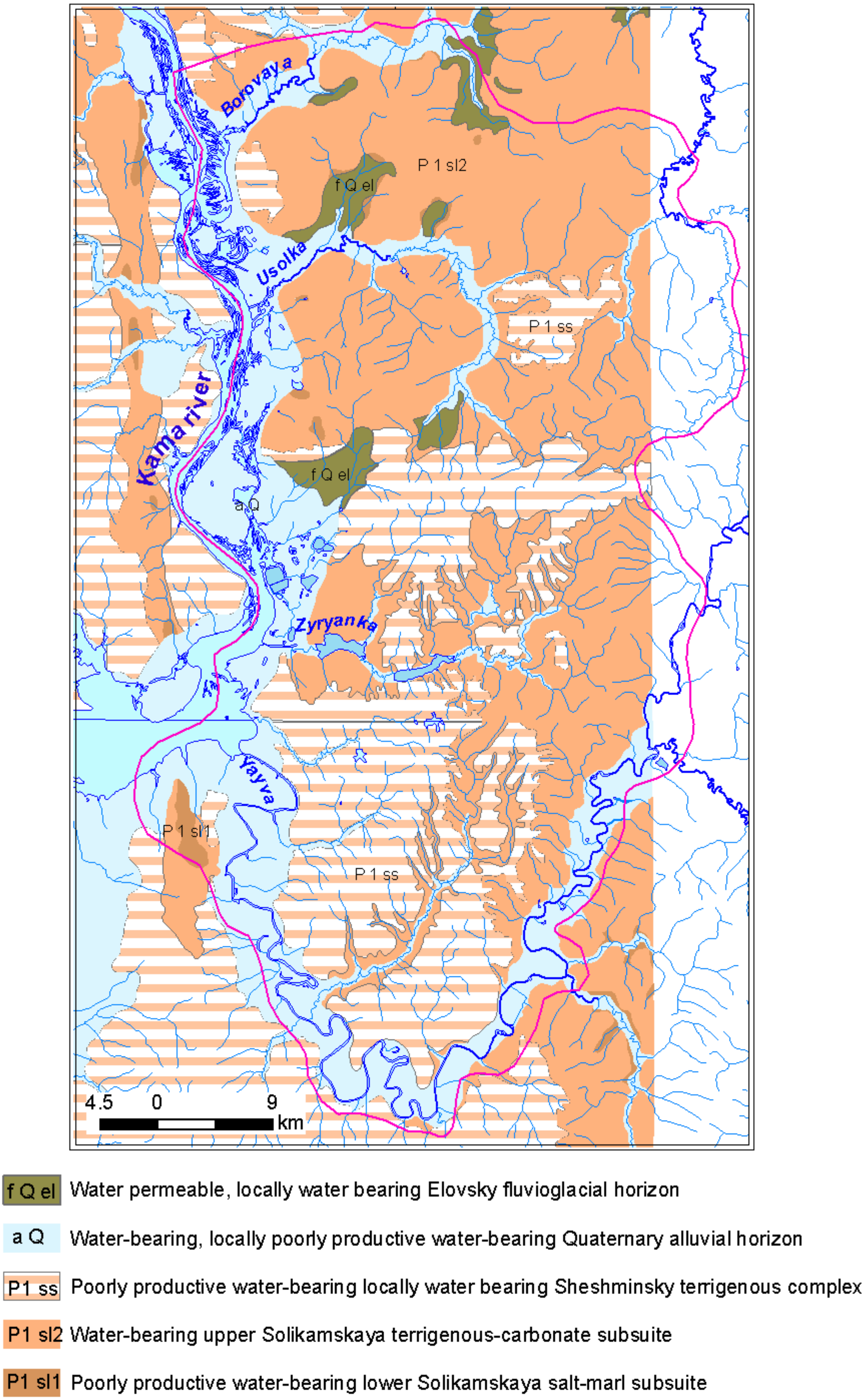


Figure 4.1. Hydrogeological map (fragment) (Haritonov et al., 2002)

Table 4.1. Thickness of alluvial deposits of rivers in the investigated area (Haritonov et al., 2002)

Placement	Alluvial thickness, m	Source of information
the Vishera river, village Anikovskaya, well. 25_V	10,5	Revin, 1988f
the Borovaya river, well. 4_{VI},5_{VI},12_{VI}	12,0-34,0	Baldin, 1998f
the Yayva, vill. Belaya Pashnya	5,6-15,0	- « -
the Kama river, to the south of Popovo	43,5	Melekhov, 1975f
the Kama river, village Tyulkino	25,0	- « -
the Kama river, Usolye town (southern suburb)	21,0	- « -
the Zyryanka river, Syeminskiy pond	16,0	- « -
the Usolka river	9,0 - 11,0	Wells record-cards
the Yayva river, village Yayva	22,9	Popovtsev, 1968f

The main part of underground waters is located in sand-gravel-pebble deposits of low accumulative terraces of the Kama river and its inflows. Groundwater pressure in some areas is caused by roughness of the subface of waterproof loams and clays overlying the sands, and does not exceed some meters. The alluvial aquifer in the research area is underplayed by Sheshminsky water-bearing complex and subsuites of Solikamsk deposits.

Under natural regime conditions there is observed hydraulic link of unconfined groundwaters with confined groundwaters of underplaying deposits. Groundwater of Sheshminskiy, Upper-Solikamsk and Lower-Solikamsk rocks are discharged into alluvium.

The describable horizon is characterized by enough high but very irregular water abundance. Discharge of 45 observed springs are changed from 0,01 to 5,0 l/s, the most frequent discharge varies between 0,1 - 0,4 l/s.

Well production rates vary from 0,08 to 11,8 l/s when decreasing of groundwater level is 0,8 -10,9 m, specific yields vary from 0,02 - 2,1 l/s, their most frequent values vary between 0,1 - 0,2 l/s (Haritonov et al., 2002).

Filtration properties of the alluvial deposits depend on granulometric composition. Hydraulic conductivity coefficients, according to the results obtained from pumping tests, are changed from 0,1 to 59,6 m/day, transmissivity from 1 to 865 m^2/day. The highest values of these coefficients are characteristic for gravel-pebble deposits, the lowest – for clay and fine-grained sands and sandy loams.

Groundwater chemical composition of the aquifer is HCO_3, HCO_3 > Cl, rarely HCO_3 > SO_4 Ca >Na, Ca > Ma, TDS varies from 0,1 to 0,5 g/l.

Increase of TDS up to 1,5 - 5,8 g/l is observed in the areas of groundwater discharge from the underlying horizons. As a rule, chemical composition of alluvium groundwater is determined by lithology of underlying rocks, chemical composition of groundwater in the main water-bearing complexes, underrun of suprasalt brines, domestic and industrial pollution. These factors determine complex hydrochemical conditions of alluvial aquifer.

The main feed sources of the aquifer are atmospheric precipitations, underrun from water-bearing complexes of Permian deposit and surface water. Discharge occurs to the river valleys as descending springs, to river stream channels as well as to underlying aquifers.

Alluvial aquifer have substantial reserve of groundwater. Groundwater consumption of alluvial groundwaters is generally limited by satisfaction of industrial needs.

Water permeable, locally water bearing Elovsky fluvioglacial horizon – fQel

Fluvioglacial deposits are locally developed in the research area in the basin of the rivers: Borovaya, Usolka, Lenva, Bygel. Thickness of the deposits varies from 0,2 m in upper parts of watersheds to 22 m in relief lowerings. In lithological composition are presented thin- and fine-grained sands and sandy loams with the prevalent grain size 0,5 - 1,0 mm. Within low parts the horizon is fully saturated by groundwater.

Depth of groundwater varies in the limits of 0,1 - 3,8 m, absolute marks of groundwater level are changed from 160 m in watersheds to 130 m in the places of discharge.

The horizon is characterized by weak water-abundance with spring discharge from 0,01 to 0,1 l/s. Natural discharges of groundwater are usually dispersed over a large area and presented as seeps or seepage areas. Filter properties of the horizon are characterized by hydraulic conductivity 0,009 - 0,14 m/day (Melekhov, 1975), in the North of the area – 1,4 – 7,7 m/day (Revin, 1988).

Chemical composition of groundwater of the fluvioglacial deposits is often NCO3>SO4 , NCO3>Cl, Ca, Ca>Na.

The aquifers is fed by precipitations. Rarely the aquifers can be recharged in a result of waters underrun from lower-laid aquifers. Groundwater moves toward the river valleys draining the aquifer. Discharge occurs either directly in the watercourse channel, or as dispersed springs which moisturizing and bogging valleys slopes. Groundwater regime depends on the temporal distribution of precipitation. Minimum levels are observed in late March or April. The maximum rise of groundwater level occurs in May - June and September - October. The small thickness of the fluvioglacial deposits and their high hypsometric position, lack of continuous aquitards and very weak water abundance complicate the use of groundwater of the complex. Its use is within the limits of exploitation of shallow wells in small villages.

Poorly productive water-bearing, locally water bearing Sheshminsky terrigenous complex P_1ss

The complex is mainly distributed in the southern part of the Upper Kama salt deposit. Northward of Solikamsk latitude it has fragmentary development, occupying the areas between the rivers of Borovaya-Glukhaya, Vilva and Borovaya-Klestovka. Water-bearing rocks (limestones, sandstones, siltstones) lie in the form of interlayers and lenses with different thickness, the main water-bearing rocks are represented by sand-stones (66% of springs are connected with sandstone outcrops. Non-fractured argillites and siltstones are aquitard deposits

In the vertical section water-bearing layers are distributed irregularly. Their highest frequency is observed until the depth of 60-80 m. Lower, in connection with decline of fracturing, the frequency of watery fluxes decreases. The exception is the wells drilling in the zones of tectonic disturbances.

In the upper part of the complex, upper the local erosional downcutting, there are presented unconfined fractured waters, lower - confined fractured waters.

The unconfined fractured waters are usually non-pressure or have local pressure due to lithology-facial heterogeneity of the profile. Depth of groundwater depends on roughness of relief and varies from 0 to 60 m, rising from the river valleys to watersheds (Figure 4.2). In the areas with "suspended" aquifers, connected with local aquitards, there is observed the deviation from this regularity.

The confined fractured waters, depending on their position in relief, are revealed by drilling on depths 10-100 m. The grounwaters are semi-confined. The pressure increases with depth of the aquifer from 5-10 to 50-100 m and more. Sometimes the wells have artesian discharge (Moshkovskiy et al., 1968).

Water abundance of the complex is not high, it is connected with predominance of the low-filtration ability of rocks in the profile. Discharges of springs vary from tenths to 30 l/s. The prevailing values of discharge do not exceed 0,3-0,5 l/s. Springs with large discharge are connected with positive local structures; in depressions their discharge decrease sharply.

Specific yield of wells in the river valleys reaches 4-5 l/s and in the watersheds it is reduced to tenths of a liter per second (Polovtsev et al., 1968).

Water abundance of the complex is characterized by considerable heterogeneity both in its square and in its section. The large fluctuation of springs and wells discharges are evidence of it. Springs discharges vary from 0,03 l/s to 20 l/s (with typical values 0,1-1,0 l/s), wells yield – 0,1 - 18,3 l/s, in case of drawdown of 0,5 -68,0 m the specific yields correspond to 0,01 -7,1 l/s (Haritonov et al., 2002).

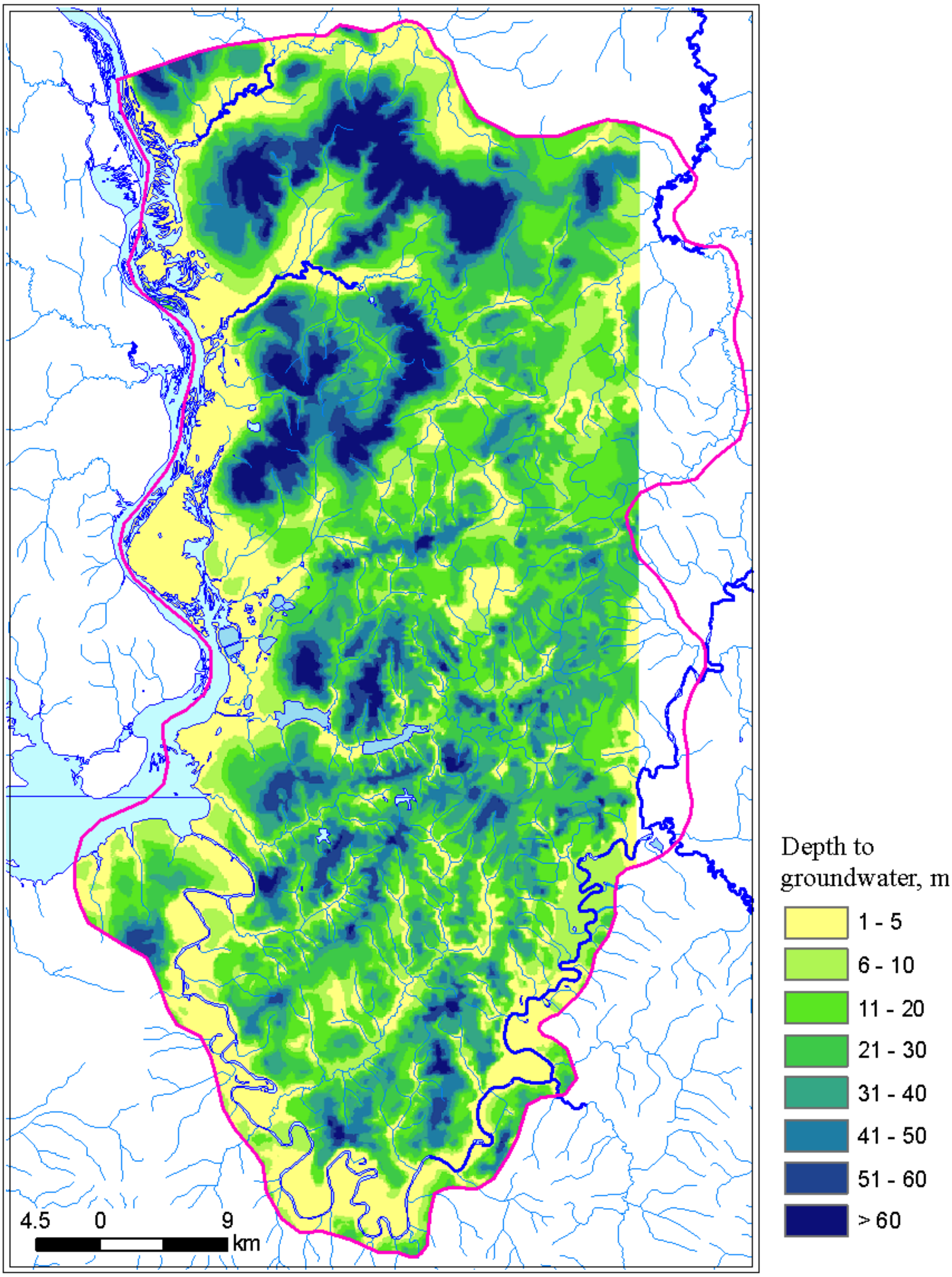


Figure 4.2. Map of the depth to groundwater level (prepared by the author)

Generally, water abundance of the complex is not high, it is connected with the predomination of the deposits with low filtration ability in the section and its large variability is caused by lithology-facial heterogeneity of the deposits and diversity of geomorphological and structure-tectonic conditions.

Maximal water abundance of the rocks, proved by large debit of springs and wells, as well as increased modules of groundwater runoff (up to 1,7 – 2,6 l/s per 1 km^2), is observed in the areas with high fractured rocks, connected with local positive structures (confided to the Kama-Vishera swell and to the zone of its connection with Kama depression).

Transmissivity for the rocks vary from 0,1 till 998 m^2/day, depending on lithology and geomorphological position (river valley, watershed). Average transmissivity for the complex is 10-100 m^2/day.

Map of hydraulic conductivity of the aquifers composed by the author by means of generalization of archival data on the studied area (Baldin, 1998, Haritonov, 2002, etc.) is presented in Fig. 4.3.

The filtration properties are decreasing with the depth in a result of reduce of effective fissuring. The highest frequency of groundwater inflows are fixed up to the depth of 80 – 120 m.

Groundwater, laying above the erosional downcutting in the washed upper part of the complex, have even chemical composition with the predominance of HCO_3 Ca>Mg and Ca > Na. Its TDS reaches 0,5 g/l. Composition of groundwater, located lower than drain influence of river net, is various. Along with predominance of saltish, anion and cation mixed waters (SO_4-Cl-Ca-Na, Cl-SO4-Na, HCO3-SO4-Na-Ca) with the TDS of several grams, there are occurred both fresh HCO_3>Cl Na, HCO_3 - Na (TDS 0,5-0,6 g/l) and highly mineralized Cl - Na (TDS 16,5-24,4 g/l) groundwater.

Water-bearing upper Solikamskaya terrigenous-carbonate subsuite P_1sl_1

The suite comes to the surface in the northern part of the territory (Figure 4.1). To the south it plunges under the Sheshminsky terrigenous complex to depth usually not more than 100 meters. The suite is represented by interchange of terrigenous and carbonate rocks with interlayers of sulfates. In the upper part of the suite predominate limestones, marls, sandstones (terrigenous-carbonate strata), at the lower – clays, marls with interlayers of anhydrides and salts (clay-marl strata). Filtration properties of rocks depends on effective fracturing which determined by lithology, position of rocks in the section and structural-tectonic factors. The terrigenous-carbonate is characterized by high and at the same time irregular permeability of rocks over the area and in section . Hydraulic conductivity in the test intervals up to the depth of

100-150 m are changed from a few to several hundred meters per a day. With depth, with general reduce of rocks permeability, the filtration heterogeneity of the rocks is persisted.

The lower part of the suite represented by clay-marl strata is weak-permeable. Its filtration field is rather homogeneous.

Water-bearing rocks of the suite (fractured limestones, sandstones, marls) are alternated with waterproof clay deposits. Anhydride interlayers are appeared in clay-marl strata among waterproof rocks. Water-bearing strata with thickness of 5-10 m and more are distributed irregularly. The most quantity of water inflows to the wells is fixed until the depth of 100 m. Deeper its quantity is sharply drops.

In the upper part of suite, upper the cut of the river valleys of Borovaya, Usolka and other inflows of Kama river, there are unconfined fractured groundwater. Usually the groundwater is nonpressure, but locally has pressure connected with heterogeneity of water-bearing strata. The unconfined fractured groundwater occurs at depth no more than 40-60 m.

Confined fractured groundwater there is lower the local erosional downcutting. This groundwater is revealed by drilling on depths from 10-20 to 60-80 m and more (Fig. 4.2). The groundwater is subpressurre. The pressure increases with plunge of rocks under the Sheshminsky terrigenous complex eastward. Wells are usually self-flowing.

Solikamsk suite is not homogeneous on its water abundance. Its upper part, the carbonate-terrigenous strata, is characterized by high but highly irregular water abundance. Springs discharges vary from 0,01 to 328,0 l/s. 55 % of the springs have discharges in the limits of 1,0-15,5 l/s. Wells yields change from 0,1 to 100 l/s when drawdowns are 0,4-39,9 m. Water abundance is reduced with depth.

The lower part of Solikams suite, clay-marl strata, is weakly watered. Well yields usually do not increase 5-7 l/s in intervals of depths to 100-150 m, and at depths to 250-350 m, they make tenths of a liter per second when drawdowns are 18-20 m.

Water abundance of Solikamsk suite greatly depends on lithological structure of the rocks, structural-tectonic and geomorphological conditions and zones of fracturing. With the latests the water abundance zones are connected . These zones havin great practical value for centralized drinking water supplying. Groundwater deposits coincided with the water abundance zones (Usolye, Borovitskoye, Upper-Kama and etc.).

Coefficient of transmissivity according to wells pumping tests (made by Federal State Unitary Enterprise “Zapauralgeologia”) range from 0,2 m^2/day to 4075 m^2/day (well 9_{III} in the valley of Borovaya river).

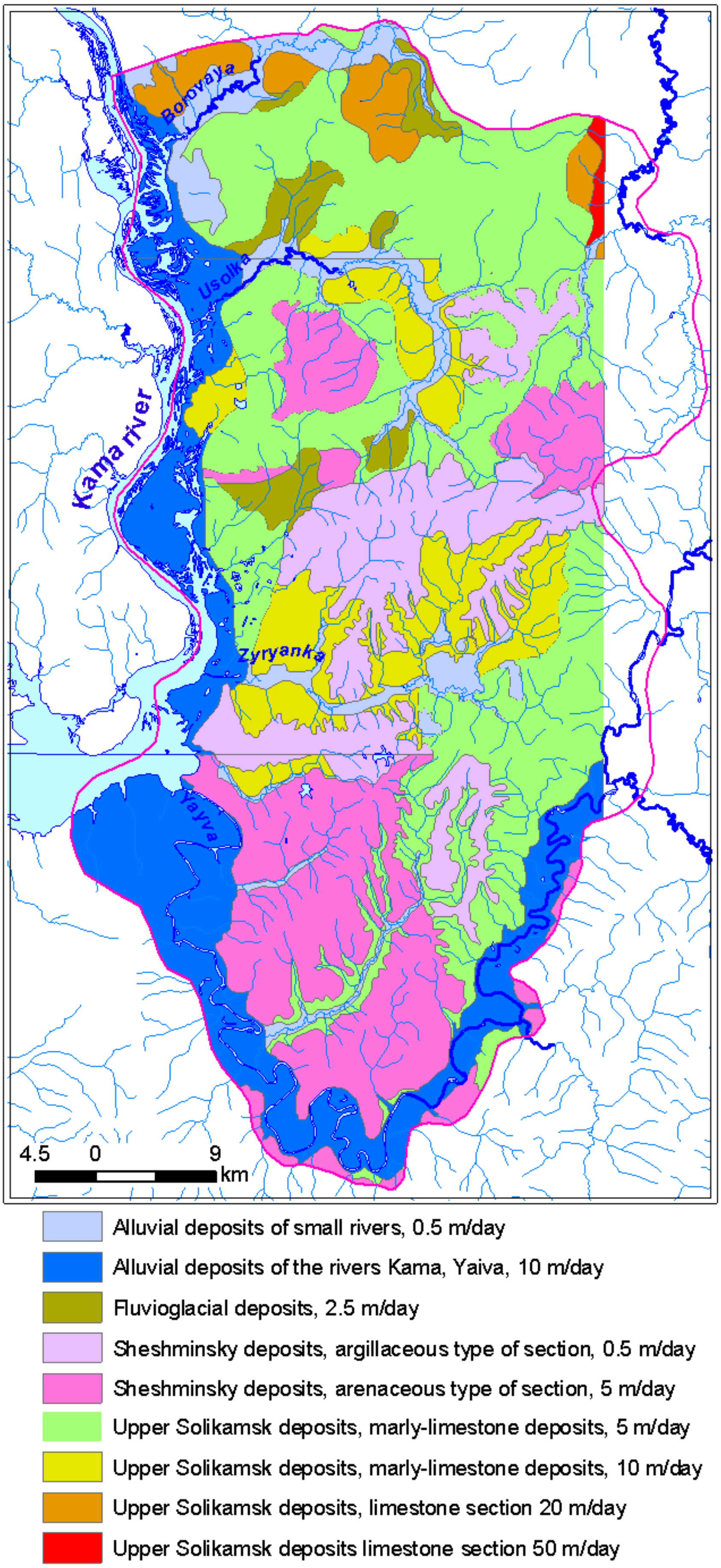


Figure 4.3. Average hydraulic conductivity values map of the aquifers (prepared by the author)

Hydraulic conductivity range from 0,003 to 81,5 m/day. The maximum values of transmissvity coefficients to 8866 m^2/day are fixed in the environs of village Glukhaya Vilva (well 2_{VIII} of deposit Surmogskoe). Background values of transmissivity for water-bearing subsuite Verhnesolikamskaya is 200 - 500 m^2/day (see also Fig. 4.3).

The suite groundwater, positioned upper than the Kama river valley, are generally fresh HCO3 Ca > Mg, Na > Ca (TDS up to 0,5-0,6 g/l). Saline waters with mainly SO_4 > Cl and Cl > SO_4, rarely SO_4 composition, with TDS 1,6-14,0 g/l are changed by chloride brines with the depth.

The boundary between fresh and saline waters lie at the depth of 100-150 m, going down on watersheds, on catchment area to great depths and rising to a depth of 50 m and less in the river valleys in the areas of saline water discharge.

Regularities of formation of regional hydrodynamics are primarily related with what spatial position is occupied by hydrogeological subdivisions relatively modern basis of drainage, which, on the territory, are represented by the river valleys.

As regards the valley of Kama river (the main drain of the region) there are two hydrogeodynamical zones. The water abundance pat of section from the level of groundwater to the Kama rive level is referred to be the zone of non-pressurized and sub-pressurized descending waters (Ostrovsky, 1985, 2001), which is characterized by free water exchange. Its aquifers are drained by the rivers of Borovaya, Usolka and etc.

Lower the drainage influence of Kama tributaries to the roofing of regional aquitard – Berezniki suite, there is located the hydrogeodynamical zone of sub-pressurized descending-ascending waters. This part of section is under drain influence of the Kama valley. Water-bearing subdivisions are laid in difficult water exchange conditions.

In the lowest part, in depressions on the surface of Bereznikovskaya waterproof strata, water exchange is become close to very difficult, peculiar to deeper aquifers. It is proved by spreading of saturated Na > Cl brines.

4.2. Natural recourses of groundwater. Infiltration calculation

Infiltration feeding is the principal source of groundwater recharge of the upper aquifer. It is quantitatively expressed as infiltration rate module which determines the rate of infiltration per unit area (Lukner, Shestakov, 1976). This module depends on many factors, including climate features of the territory, relief, lithological and hydrogeological features of rocks in aeration zone, vegetation, etc. Thus, the process of infiltration is enough difficult for determination and may be explained approximately.

There are lots of methods to estimate the rate of infiltration: nature observation methods (measurement with lysimeters); method of estimation of infiltration rate using module of groundwater runoff (flow); methods based on hydrodynamic regime of groundwater. Every of them has advantages and disadvantages. For instance, the nature observation methods require high accuracy of determination of infiltration rate and applicable only on small balance areas. Methods for determination of infiltration rate using module of groundwater runoff give only generalized characteristics and don't take into account the heterogeneity of rock structure in the unsaturated zone. As regards the method of groundwater hydrodynamics regime, for the estimation with use of this method, huge volume of expensive drilling activities is needed. Also it is necessary to note a method of determination of infiltration and evaporation regularities basing on the theory of moisture transfer in the unsaturated zone (Lukner, Shestakov, 1976).

To estimate the infiltration rate of the area under research there was applied the method of estimation by using module of groundwater runoff. The module of groundwater runoff (l/sec*km^2) is the ratio between the total value of groundwater discharge and square of the drainage basin. Having data on modules of groundwater runoff for a research area, it can be evaluated the natural groundwater resources of the area. Besides, the data on modules of groundwater runoff allow to reflect non-homogeneity of formation of such runoff in the investigated aquifer. Groundwater runoff formation researches have been conducted in Russia for a long period of time. Lots of science publications are dedicated to the regional estimation of groundwater runoff by Russian scientists B.Kudelin, I.Zektser, V.Vsevolozhskiy, I.Fidelli, R.Dzhamalov, V.Klimenko, N.Lebedeva, R. Kochetkova and etc.

When estimating modules of groundwater runoff, the widely used method is a method based on a study of the low-water flow of rivers (Zektser I.S., 2007). Its essence consists in taking into account the concrete hydrogeological conditions of river basins and regularities of groundwater runoff into a river from all aquifers of drainage zone. In some cases, a value of groundwater runoff may be approximately determined by calculation of a variation of the low-water flow of a river on a section between of two hydrometric river stations. The value of variation of the river flow within a river section without tributaries (or minus the sum of tributaries discharge), determined during the stable low water period, is the value of groundwater runoff from drainage aquifers or the value of groundwater recharge for account of river flow intake.

A river low water flow is formed within the period of its stable feeding for account of groundwater discharge from the zone of intensive water exchange, when the surface runoff lack or does not influence on a river flow essentially. Thus, it is considered that groundwater discharge is equal to groundwater runoff, formed on the catchment area, upper the estimated hydrometric river stations for the period of its stable feeding by groundwater.

Map of modules of groundwater runoff for the territory of the Upper Kama salt deposit is presented in Fig. 4.4. It reflects the amount of natural groundwater resources of the studied area.

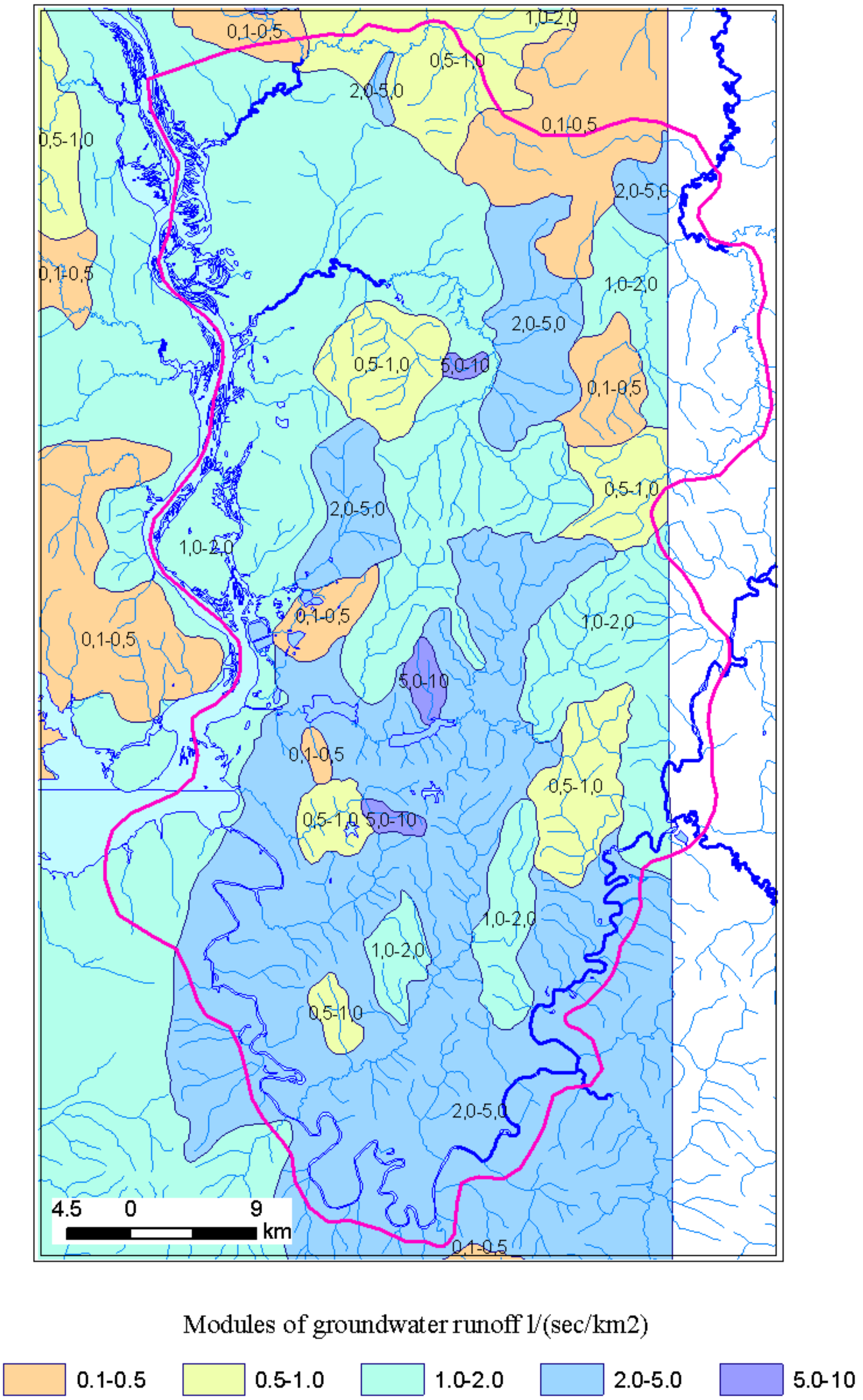


Figure 4.4. Map of modules of groundwater runoff. Natural recourses of groundwater (Haritonov et al., 2002)

Value of infiltration rate is closely connected with the module of groundwater runoff and is determined by the formula:

$$W = 31{,}5M$$

where W – infiltration rate (mm/year), M – module of groundwater runoff (l/sec*km^2), 31,5 – coefficient, taking into account the dimension of the equation parameters.

On the basing of the performed calculations, there were received the following values of infiltration rate (see Figure 4.5).

The value of natural resources of groundwater, expressed by the module of groundwater runoff, on 80% of the studied area is on average of 1.5 – 3.5 1 / sec ·km^2 (Figure 4.5). On approximately the half (43%) of the territory the value of module of groundwater runoff changes from 1 to 2 l/s·km^2, on the another smaller (39%) part – from 2 to 5 l/sec·km^2. On the rest part of the territory (about 17% of the area) value of groundwater runoff is less than 1 l/sec·km^2.

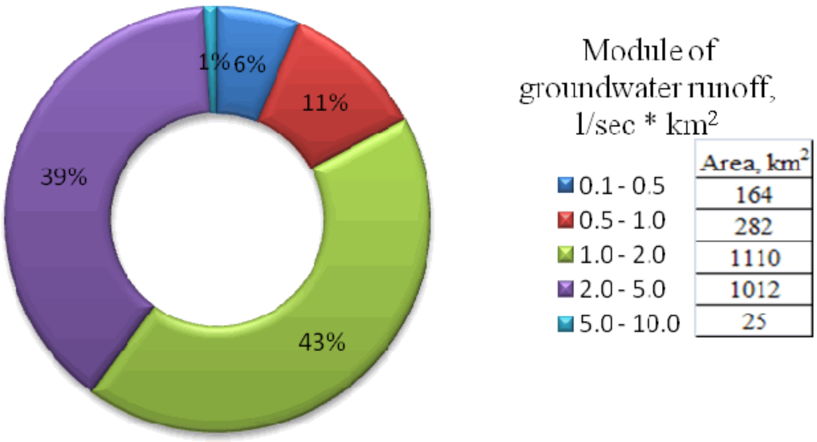
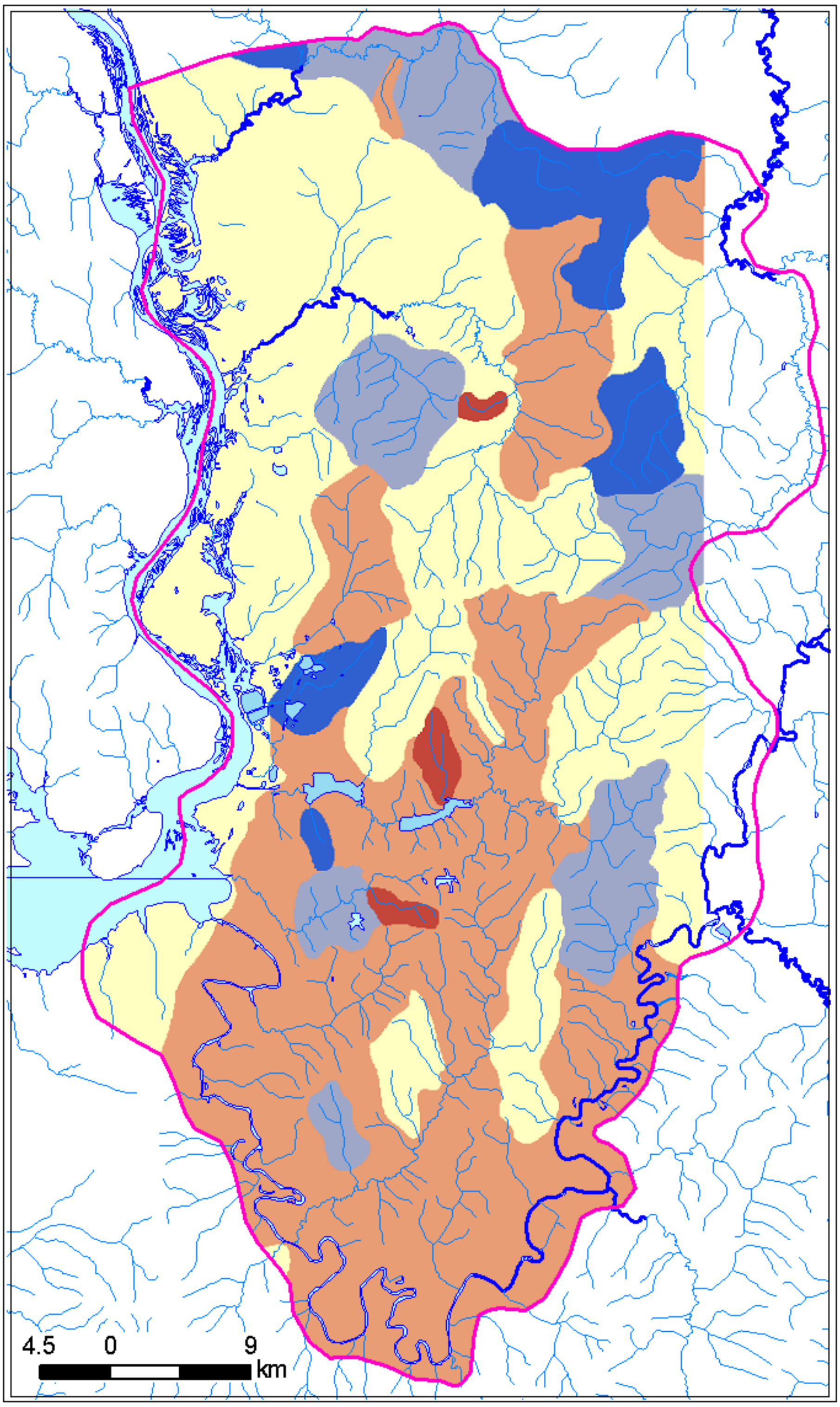


Fig. 4.5. The distribution of natural groundwater resources on the territory

Natural groundwater resources of Sheshminsky water-bearing complex make up on average 2-5 l/s·km^2 (Table 4.2), resources of Solikamsky terrigenous-carbonate complex and alluvial horizons – 1 to 2 l/sec ·km^2. In the valley of r. Yayva the resources of alluvial horizon are increased to 2-5 l/sec·km^2.

Table 4.2. Natural groundwater resources of aquifers (mean values)

Index of the aquifer	Area, км^2	Mean module of groundwater runoff, l/sec*km^2
f Qel	74	1.0 - 2.0
aQ	691	1.0 - 2.0
P_1 ss	688	2.0 - 5.0
P_1 sl_2	1122	1.0 - 2.0
P_1 sl_1	16	1.0 - 2.0



Effective infiltration, mm/year

< 16 | 16 -32 | 32 -63 | 63 - 158 | 158 - 315

Figure 4.5. Map of effective infiltration (mm/year) values

CHAPTER 5

COMPARISON OF RESULTS OF THE GROUNDWATER VULNERABILITY ASSESSMENT PERFORMED BY DIFFERENT METHODS, AND DEVELOPMENT OF RECOMMENDATIONS AS WELL AS CONDITIONS OF THEIR APPLICATION

Medium-scale (M 1:100000) vulnerability assessment of groundwater used for drinking water supply was carried out for the entire area under study (Figure 3.1). Vulnerability assessment was carried out by two methods. In the first case there was given a qualitative assessment of vulnerability for investigated area on the basis of method SINTACS using the data of depths of groundwater, effective infiltration, lithological composition of rocks of the unsaturated zone, characteristics of soils, lithological composition of the aquifer and its filtration properties and topographic slopes of the earth's surface. The characteristics of these parameters are described in Chapters 3 and 4 of this thesis.

In the second case, an assessment of the travel time during of which the concentration of Cl-ion come with technogeneous brines from the earth's surface to the aquifer reaches the values of MPC (MPC for Cl in Europe, 0.25 g / l, in Russia – 0.35 g / l) was carried out.

The unsaturated zone on the study area has two-layer structure. The upper layer is presented by Quaternary deposits of different genesis, the lower – by the Permian bedrock. These structural features were taken into account when assessing of the vulnerability by both methods. When assessing the vulnerability by the method SINTACS, the estimation of parameter «N» for the Quaternary deposits was made as for the weighted average thickness. For the second case, the calculations of the travel time of Cl-ion were carried out separately for the upper and lower layer.

When assessing of the vulnerability by method SINTACS, the maximum values of infiltration were taken into account. For the second method, calculations were performed for the minimum and the maximum values of infiltration that allowed to estimate the role of the infiltration as a crucial factor of the groundwater vulnerability.

5.1. Assessment of groundwater vulnerability by SINTACS method

Prior to proceed directly to the description of the data processing for assessing of vulnerability by the SINTACS method, we consider the brief descriptions of the parameters that are taken into account (Table 5.1). In the corresponding cells of the table there are shown the graphs and charts for determinating of the rating value for the seven SINTACS parameters (depth to groundwater, infiltration, lithological features of the unsturated zone, the nature of the soil cover, lithology of the aquifer and its filtration properties, and topographic slopes of the area) (see also Fig. 5.3).

DEPTH TO GROUNDWATER (S). The scheme of ranging of depths to groundwater is shown in Fig. 5.4. The initial map of depths to groundwater, prepared by the author, is presented in Fig. 4.2. For the convenience of ranking of depths to groundwater there was set up an approximating equation (Fig. 5.5). The intervals of depths and ratings corresponding to SINTACS are given in Table 5.2. As can be seen on the histogram (Fig. 5.4), the predominant values of ratings are 2 and 3 (depth varies from 19.50 to 60 m) and 10 (depth is less than 1 m).

EFFECTIVE INFILTRATION ACTION (I). The Table 5.3 shows the values of the effective infiltration and the corresponding values of rating SINTACS. Areal distribution of sites with different values of infiltration is represented in Fig. 5.6. As already noted above, to assess the vulnerability by the method SINTACS there have been used the maximum values of infiltration. The predominant rating values for the study area are 3 and 7 with values of infiltration respectively 63 and 158 mm / year.

UNSATURATED ZONE ATTENUATION CAPACITY (N). The unsaturated zone in researched area has a double-layer structure (see Figure 5.7). The upper layer is presented by the Quaternary deposits, the lower layer - by the Permian deposits. Taking into account the geological data of more than 400 wells in the studied area, the author has prepared a map of thickness of the Quaternary deposits (Fig. 5.8). And knowing depths to groundwater (or thickness of unsaturated zone), the thicknesses of the unsaturated pat in both the upper (Quaternary) layer (Fig. 5.9.) and the lower (Permian) layer (Fig. 5.10.) were determined. Approximately 40% of the territory has a single-layer unsaturated zone composed by the Quaternary deposits only. Characteristics of deposits of the upper and the lower layers of the unsaturated zone are given in Tables 5.4 and 5.5. In Fig. 5.11 and 5.12 there are shown the values of ratings, respectively, for the upper and the lower layers of the unsaturated zone. The Fig. 5.13 is the final scheme reflecting the parameter «N» of SINTACS. It was defined as the weighted average of the two layers with a glance of thickness of each layer.

SOIL/OVERBURDEN ATTENUATION CAPACITY (T). Characteristics of soils are given in Table. 5.6. In the table there are also given various types of soil according to Kachinsky classification (commonly used in Russia) and their equivalents in Ferre triangle that accepted in European countries (Fig. 5.14). Distribution of soil types in accordance with the rating SINTACS is shown in Fig. 5.15.

HYDROGEOLOGIC CHARACTERISTICS OF THE AQUIFER (A). HYDRAULIC CONDUCTIVITY RANGE OF THE AQUIFER (C). Characteristics of water-bearing rocks, as well as ranging of the parameters «A» and «C» according to SINTACS is presented in Table. 5.7. The ranking of these parameters is also shown in Fig. 5.16 and Fig. 5.17. As is obvious from the Fig. 5.17, the predominant range of values of the hydraulic conductivity varies from 5 to 10 m/day.

HYDROLOGIC ROLE OF THE TOPOGRAPHIC SLOPE (S). Slopes of land surface (in %) are shown in Fig. 5.18. Matching of the slopes to SINTACS ratings can be seen in Fig. 5.19. The prevailing values of the slopes of the territory are ranked from 0 to 2% (the rating "10" in SINTACS).

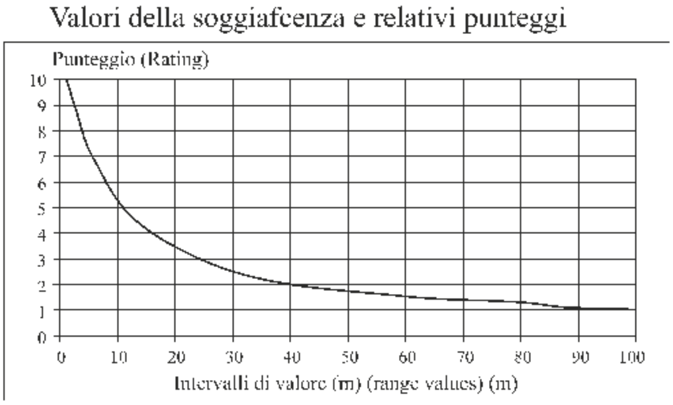
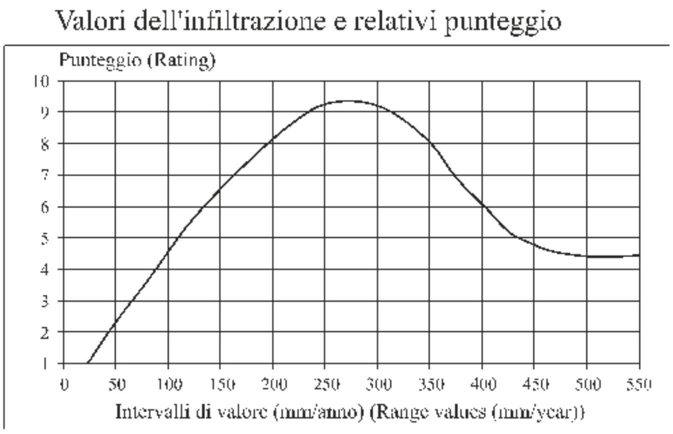
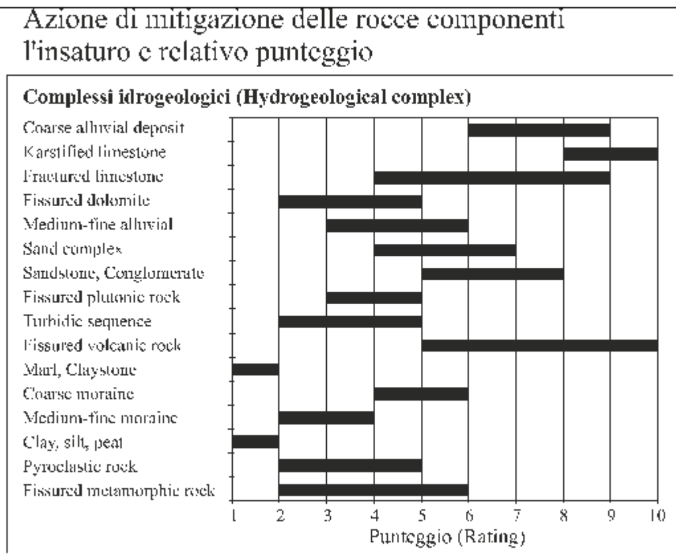
In the studied area, according to the method SINTACS, there were marked out areas with different anthropogenic impact (Fig. 5.1). The areas of the salts deposit which are developed as well as the sites where situated oil deposits have been referred to the zones with high anthropogenic impact. The river network (the Kama river with the main tributaries) including the buffer zones characterized by extension of the alluvial aquifer was set as a drainage zone (Fig. 5.20). The weights for all the parameter layers considerated by the method SINTACS have been assigned in accordance with the diagram in Fig. 5.1 and presented in Fig. 5.21.

On the next stage, there was calculated the vulnerability indices by the formula (2) in Chapter 2 of this thesis. The final ranking of the vulnerability indices was carried out in accordance with the diagram 5.2.

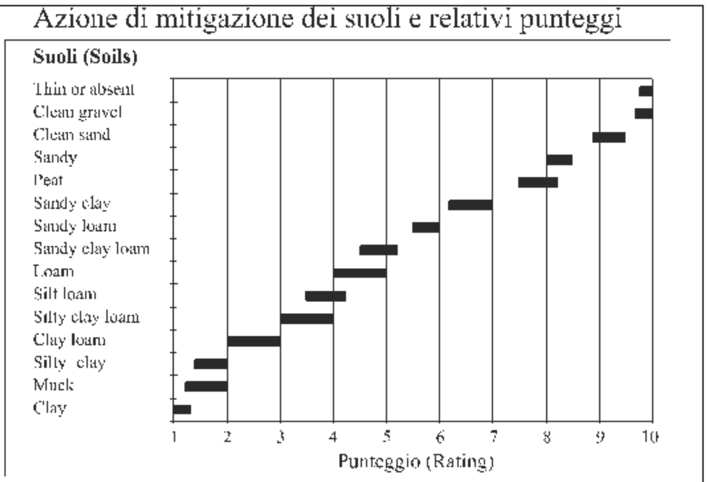
The resulting scheme of the groundwater vulnerability by the method SINTACS is presented in Fig. 5.22. As it is evident from the chart at the bottom of the figure, the areas with moderate and high groundwater vulnerability degree are predominated in the studied territory.

Table 5.1. Description of the parameters and related rating graphs for SINTACS

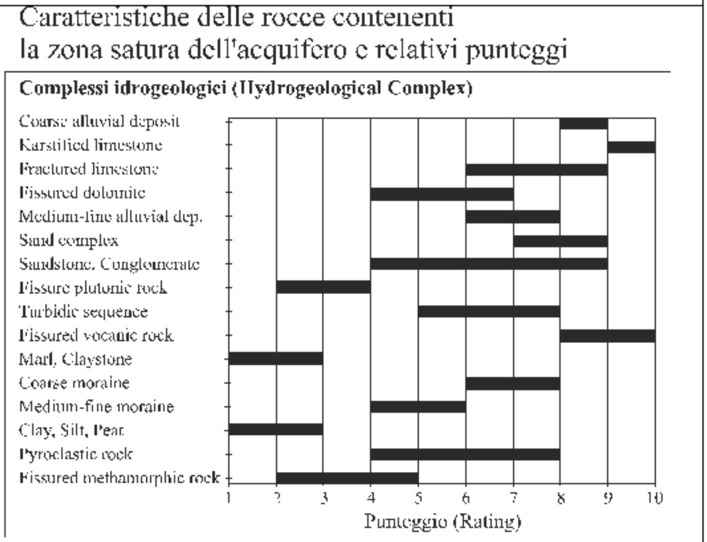
(Civita M., De Maio M., 2004)

Description	Rating Definition
DEPTH TO GROUNDWATER: is defined as the depth of the piezometric level (both for confined or unconfined aquifers) with reference to the ground surface and it was a great impact on the vulnerability because its absolute value, together with the unsaturated zone characteristics, determine the time of travel (TOT) of a hydro-vectored or fluid contaminant and the duration of the attenuation process of the unsaturated thickness, in particular the oxidation process due to atmospheric O_2. The SINTACS rating of depth-to-groundwater therefore decreases with an increase of the depth, i.e. with an increase of the thickness of the unsaturated zone.	
EFFECTIVE INFILTRATION ACTION: The role that the effective infiltration plays in aquifer vulnerability assessment is very significant because of the dragging down surface of the pollutant but also their dilution, first during the travel through the unsaturated zone and then within the saturated zone. Direct infiltration is the only or widely prevalent component of the net recharge in all the areas where there are no interflow linking aquifers or superrficial water bodies or no irrigation practices using large water volumes.	
UNSATURATED ZONE ATTENUATION CAPACITY: The unsaturated zone is the "second defense line" of the hydrogeologic system against fluids or hydro-vectored contaminants. A four dimension process takes place inside the unsaturated thickness in which physical and chemical factors synergically work to promote the contaminant attenuation. The unsaturated zone attenuation capacity is assessed starting from the hydrolithologic features (texture, mineral composition, grain size, fracturing, karst development, etc.).	

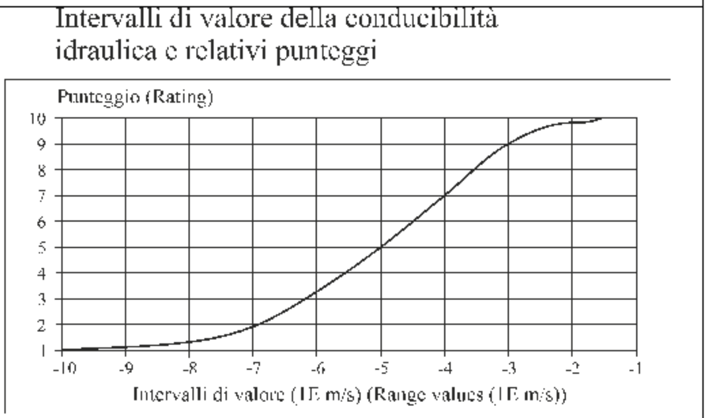
SOIL/OVERBURDEN ATTENUATION CAPACITY This is the “first defense line” of the hydrogeologic system: several important processes take place inside the soil that built up the attenuation capacity of a contaminant travelling inside a hydrogeologic system and therefore in aquifer vulnerability assessment and mapping. Soil is identified as an open, three-phase, accumulator and transformer of matter and an energy subsystem which develops through the physical, chemical and biological alterations of the bottom lithotypes and of the organic matter that it is made up of.



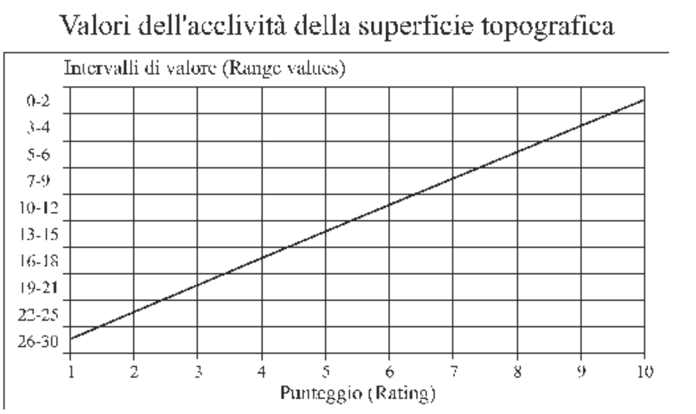
HYDROGEOLOGIC CHARACTERISTICS OF THE AQUIFER: In vulnerability assessment models, the aquifer characteristics describe the process that takes place below the piezometric level when a contaminant is mixed with groundwater with a loss of a small or more relevant part of its original concentration during the travelling through the soil and the unsaturated thickness. Basically these processes are: molecular and cinematic dispersion, dilution, sorption and chemical reactions between the rock and the contaminants.



HYDRAULIC CONDUCTIVITY RANGE OF THE AQUIFER: Hydraulic conductivity represents the capacity of the groundwater to move inside the saturated media, thus the mobility potential of a hydro-vectored contaminant which as a density and viscosity almost the same as the groundwater. In the SINTACS assessment context, the hydraulic gradient and the flux cross section being equal, this parameter deter- mines, the aquifer unit yield and flow velocity that go toward the effluences or the tapping work that indicates the of risk targets.



HYDROLOGIC ROLE OF THE TOPOGRAPHIC SLOPE: The topographic slope is an important factor in vulnerability assessment because it determines the amount of surface runoff that is produced, the precipitation rate and displacement velocity of the water (or a fluid and/or hydrovectorable contaminant) over the surface being equal. A high rating is assigned to slight slopes i.e. to surface zones where a pollutant may be less displaced under gravity action or even stop in the outlet place favoring percolation. The slope may be a genetic factor due to the type of soil and its thickness, and can indirectly determine the attenuation potential of the hydrogeologic system.



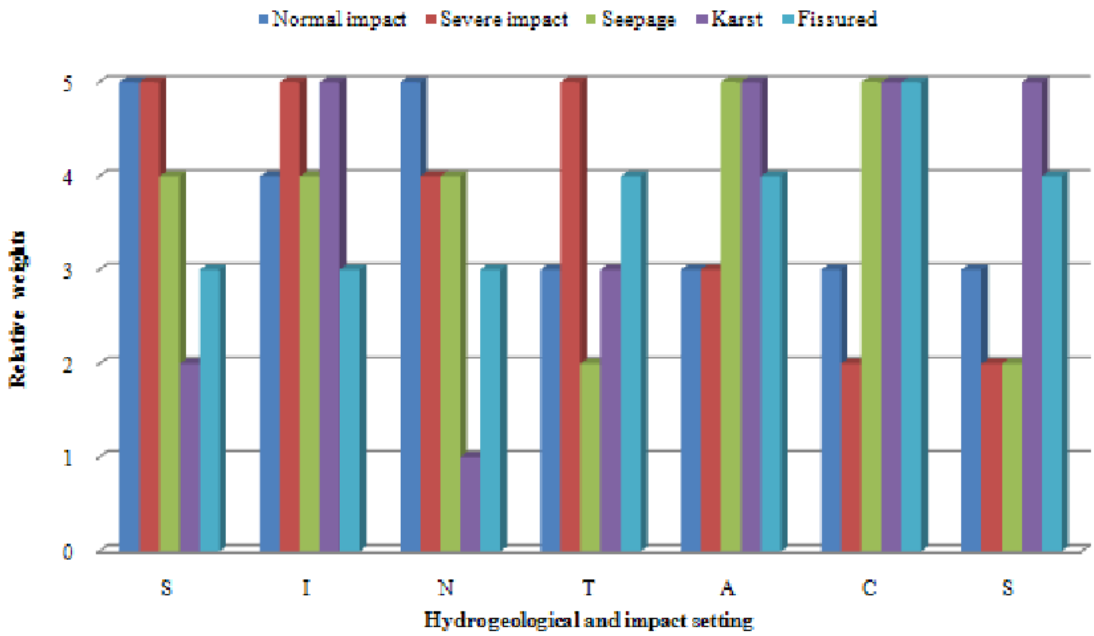
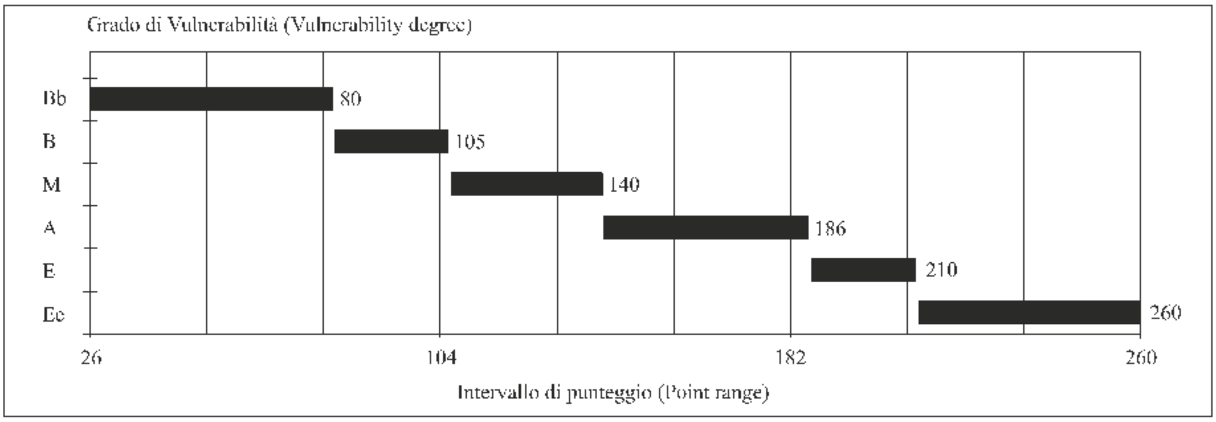


Figure 5.1. Strings of multiplier weights given for SINTACS (Civita M., De Maio M., 2004)

Intervalli/gradi di vulnerabilità intrinseca (punteggi grezzi)



Intervalli/gradi di vulnerabilità intrinseca normalizzati

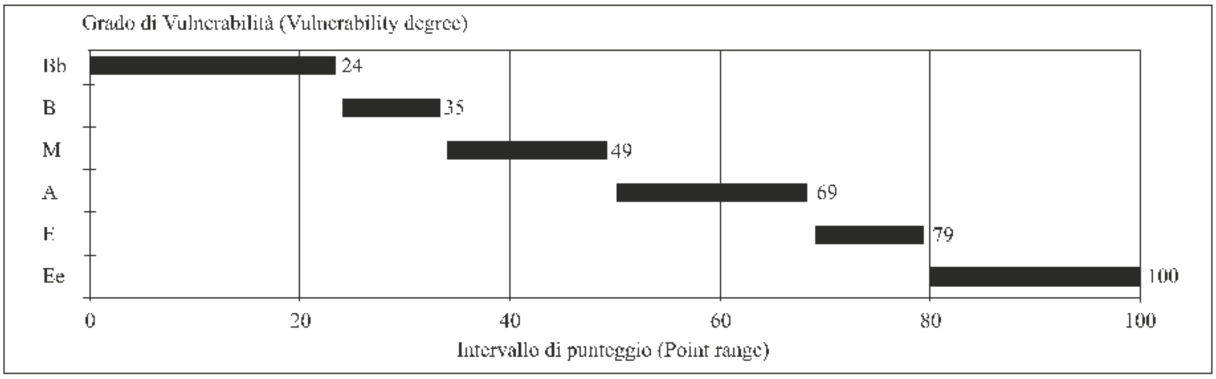


Figure 5.2. Final ranging (a) and percentualized point vulnerability degrees (b) of SINTACS index (Civita M., De Maio M., 2004)

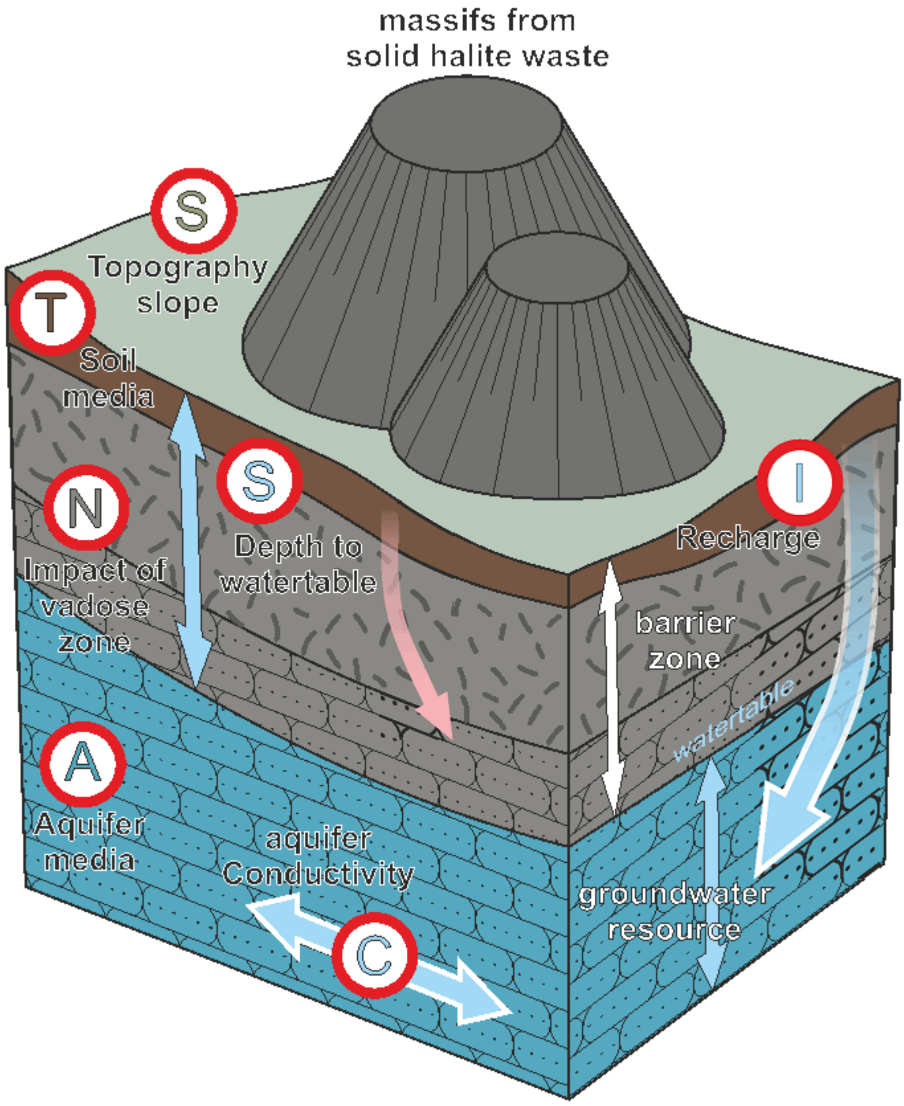


Figure 5.3. Basic scheme of groundwater vulnerability factors considered in SINTACS

S - Depth to groundwater

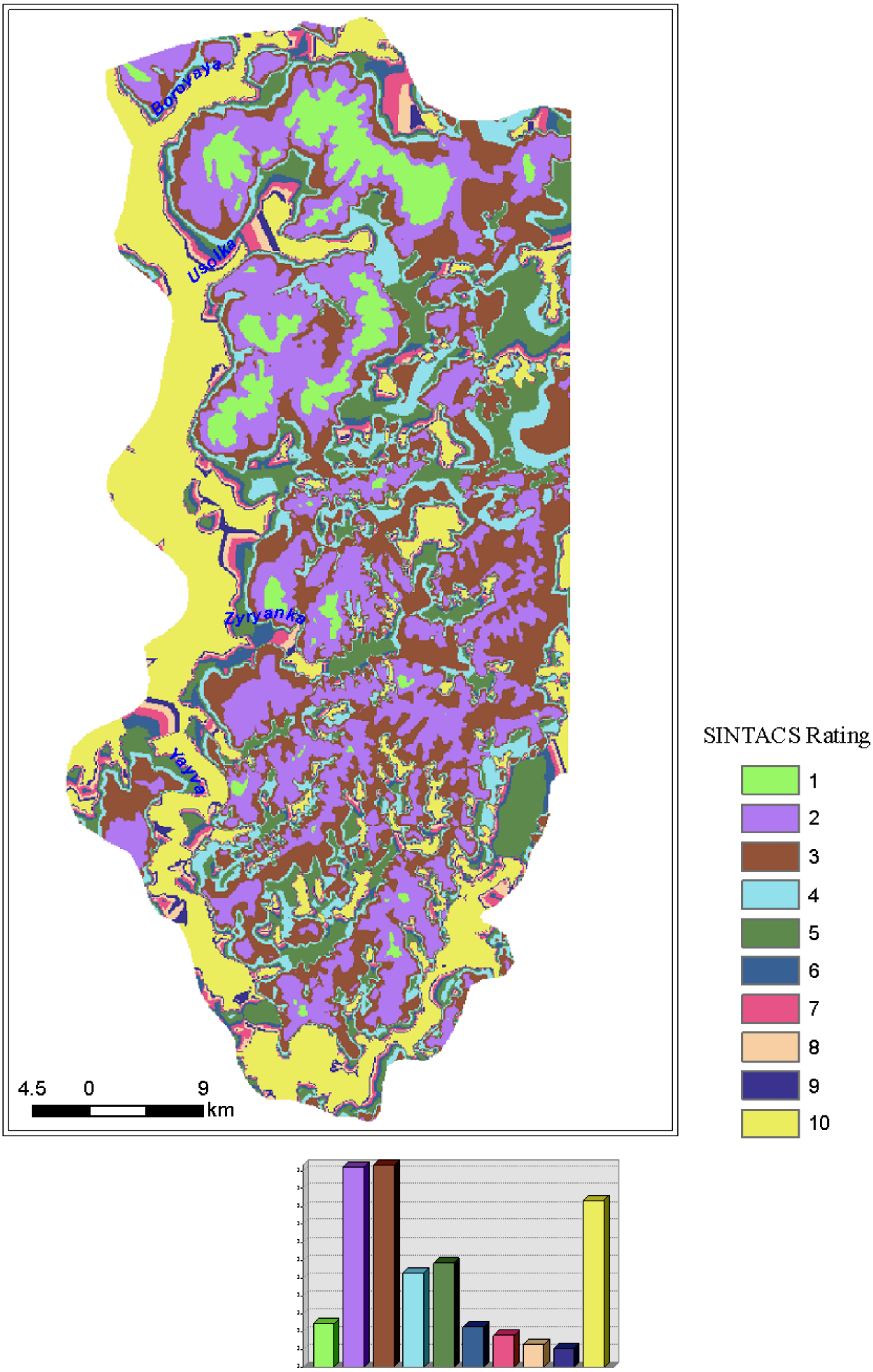


Figure 5.4. SINTACS rating of depth to groundwater level

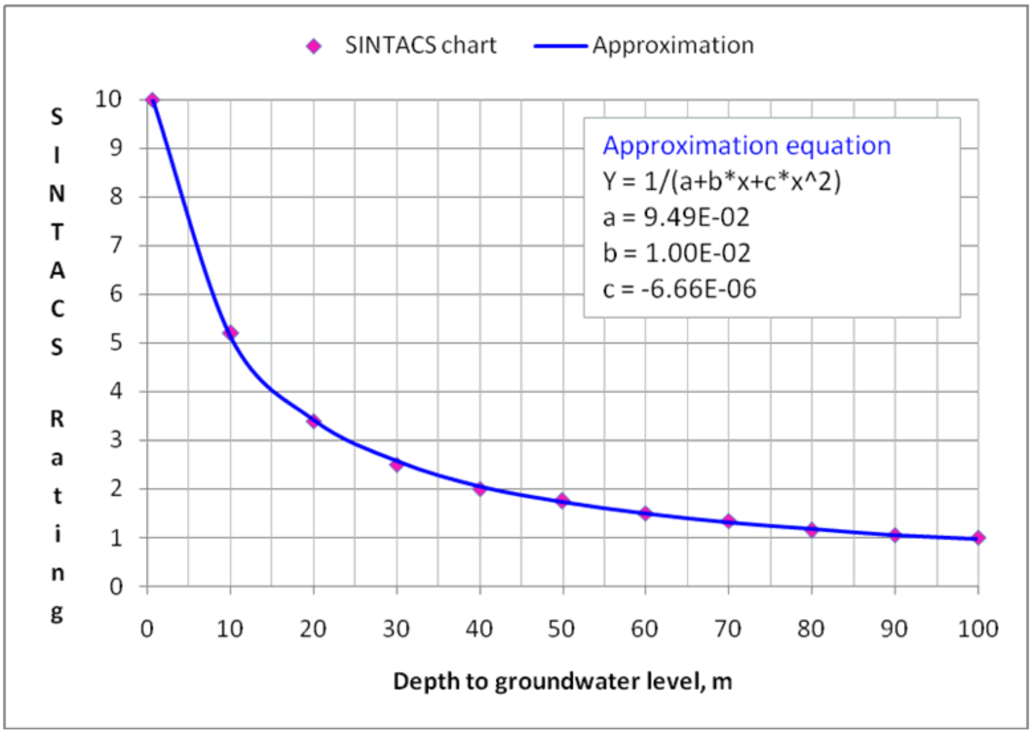


Figure 5.5. Range values and rating of depth to groundwater level

Table 5.2. Interval of depths and SINTACS rating of depth to groundwater level

Depth to groundwater level, m	Rating calculated by equation of approximation	Interval of depths to groundwater level	SINTACS Rating
0.50	10	< 1.05	10
1.05	9.49	1.05 – 2.30	9
2.30	8.48	2.30 – 3.85	8
3.85	7.49	3.85 – 5.95	7
5.95	6.48	5.95 – 8.75	6
8.75	5.49	8.75 – 12.85	5
12.85	4.49	12.85 – 19.50	4
19.50	3.47	19.50 – 31.20	3
31.20	2.49	31.20 – 60.00	2
60	1.49	> 60	1

I – Effective infiltration

Table 5.3. SINTACS rating of effective infiltration

Effective infiltration, mm/year	SINTACS Rating
315	9
158	7
63	3
32	2
< 16	1

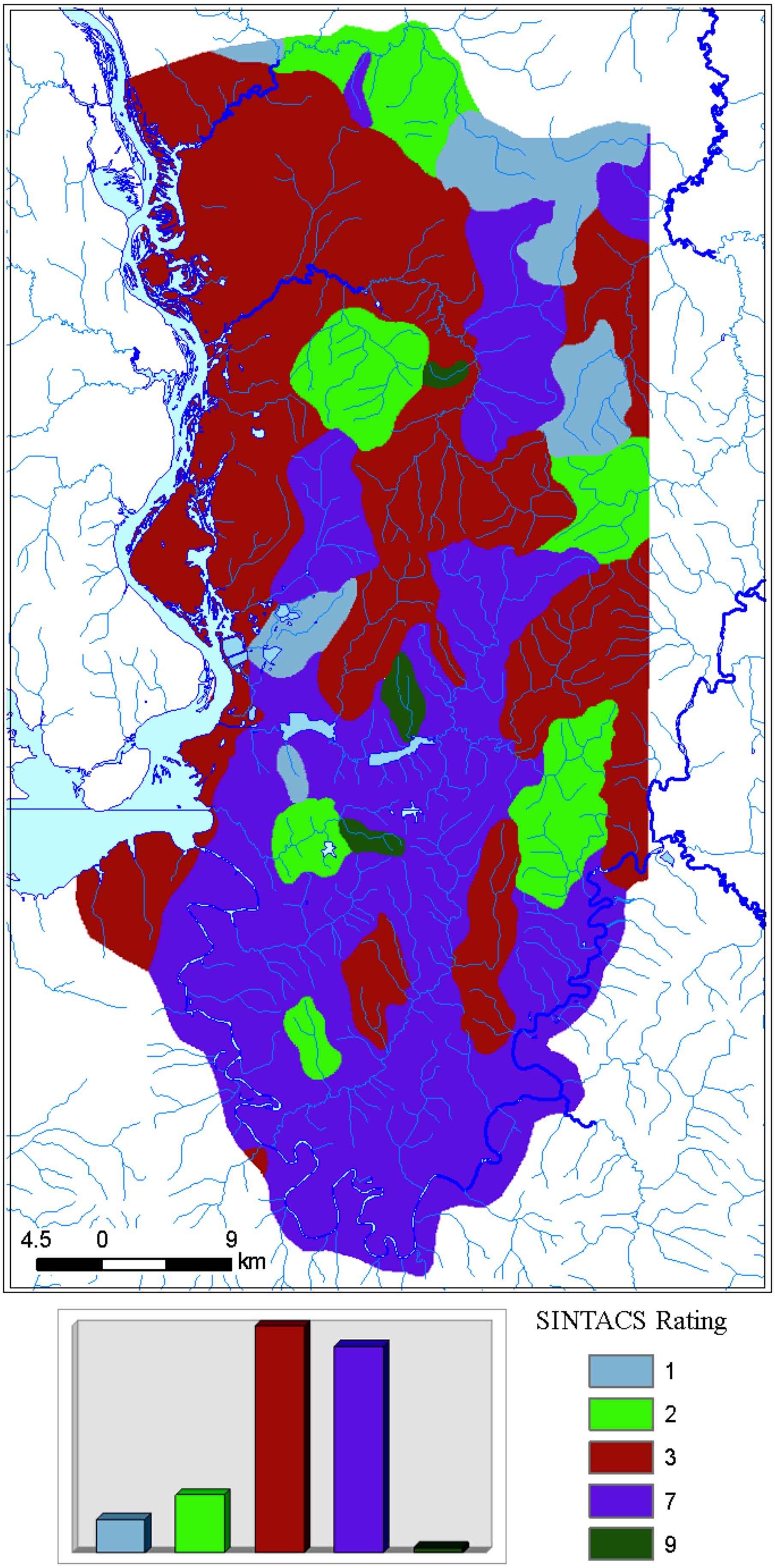
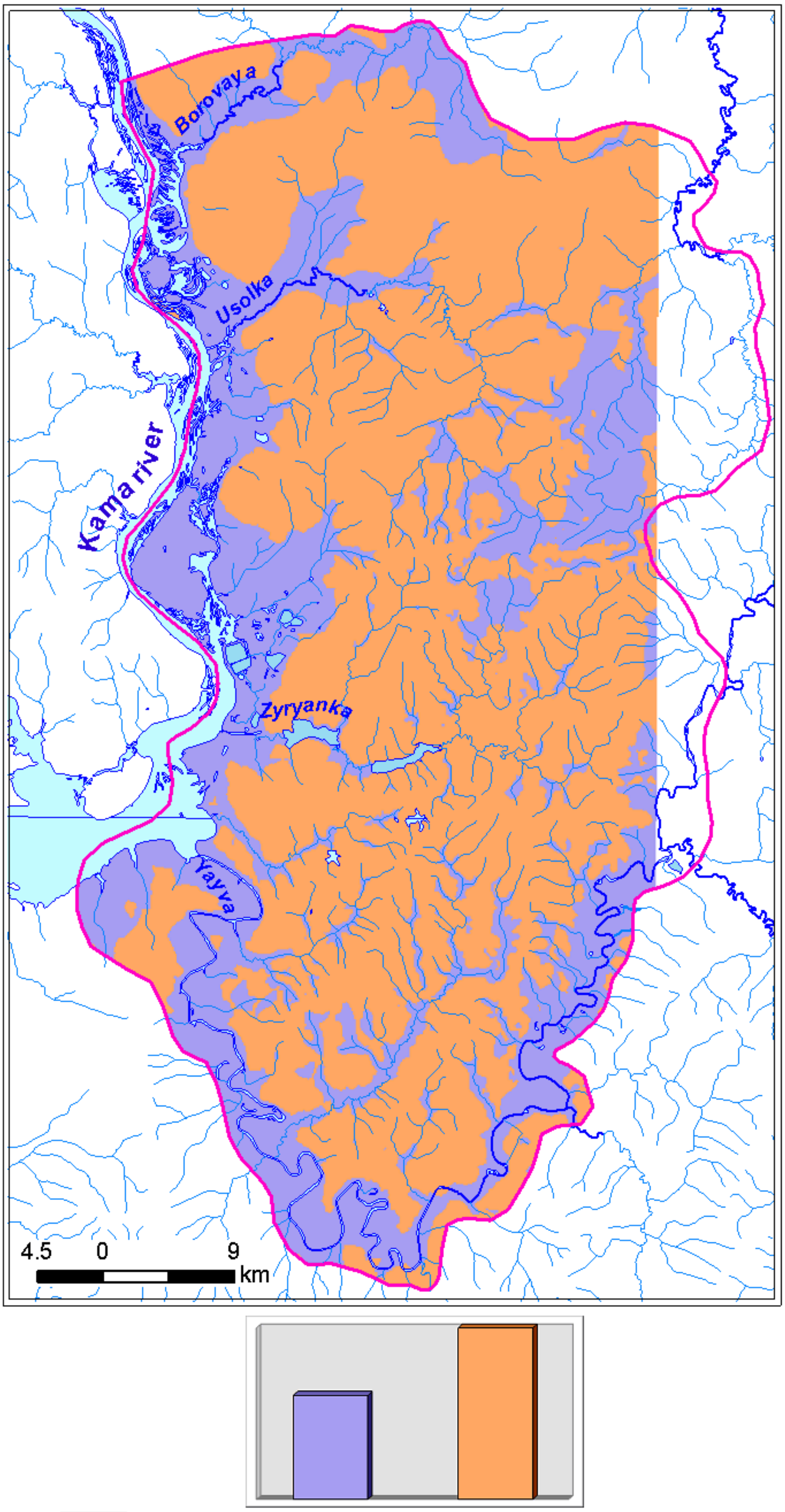


Figure 5.6. SINTACS rating of effective infiltration

N - Effect of the unsaturated zone



single-layer unsaturated zone (Quternary deposits)

double-layer unsaturated zone (Quternary and Permian deposits)

Figure 5.7. Structure of the unsaturated zone

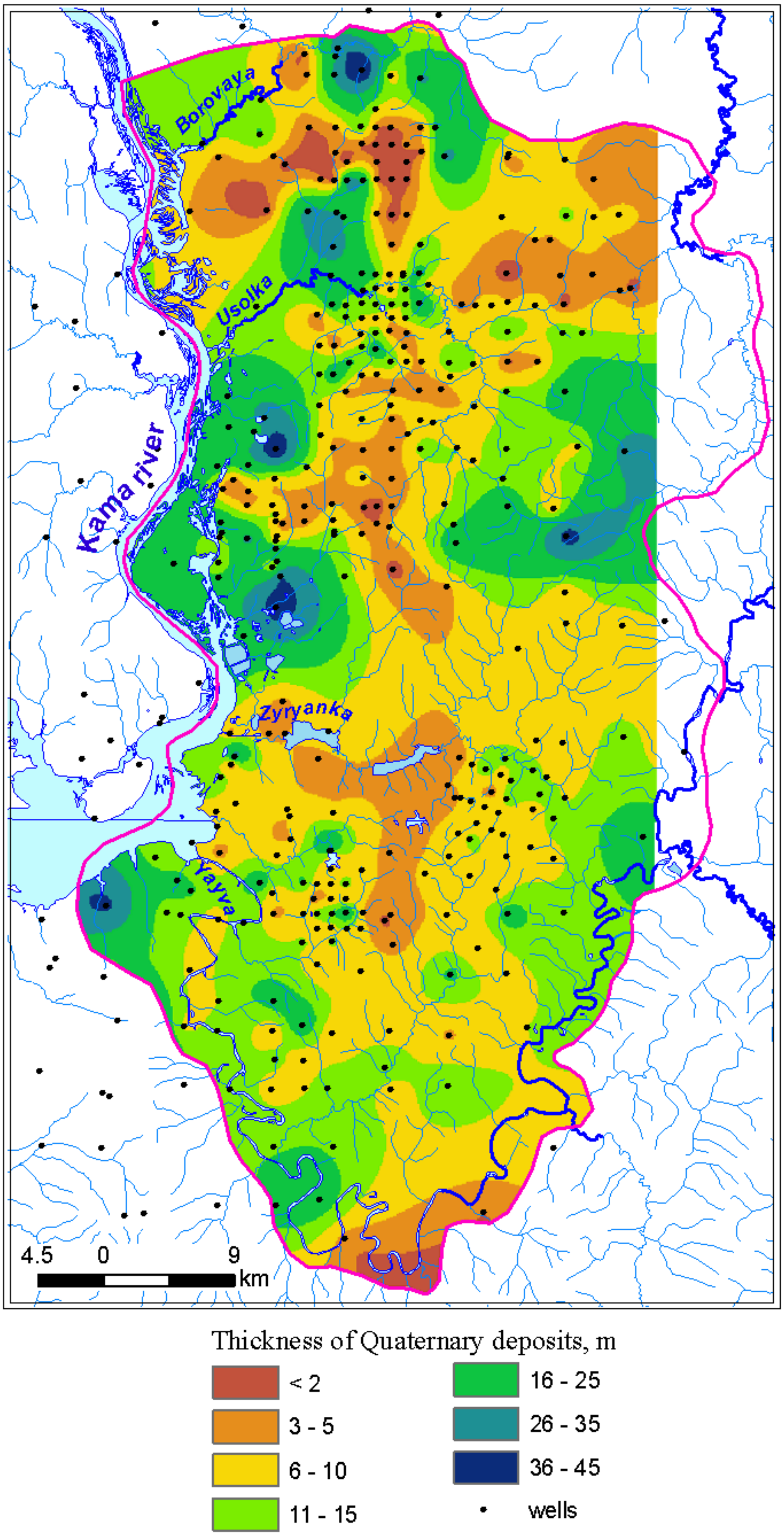


Figure 5.8. Map of thickness of the Quaternary deposits

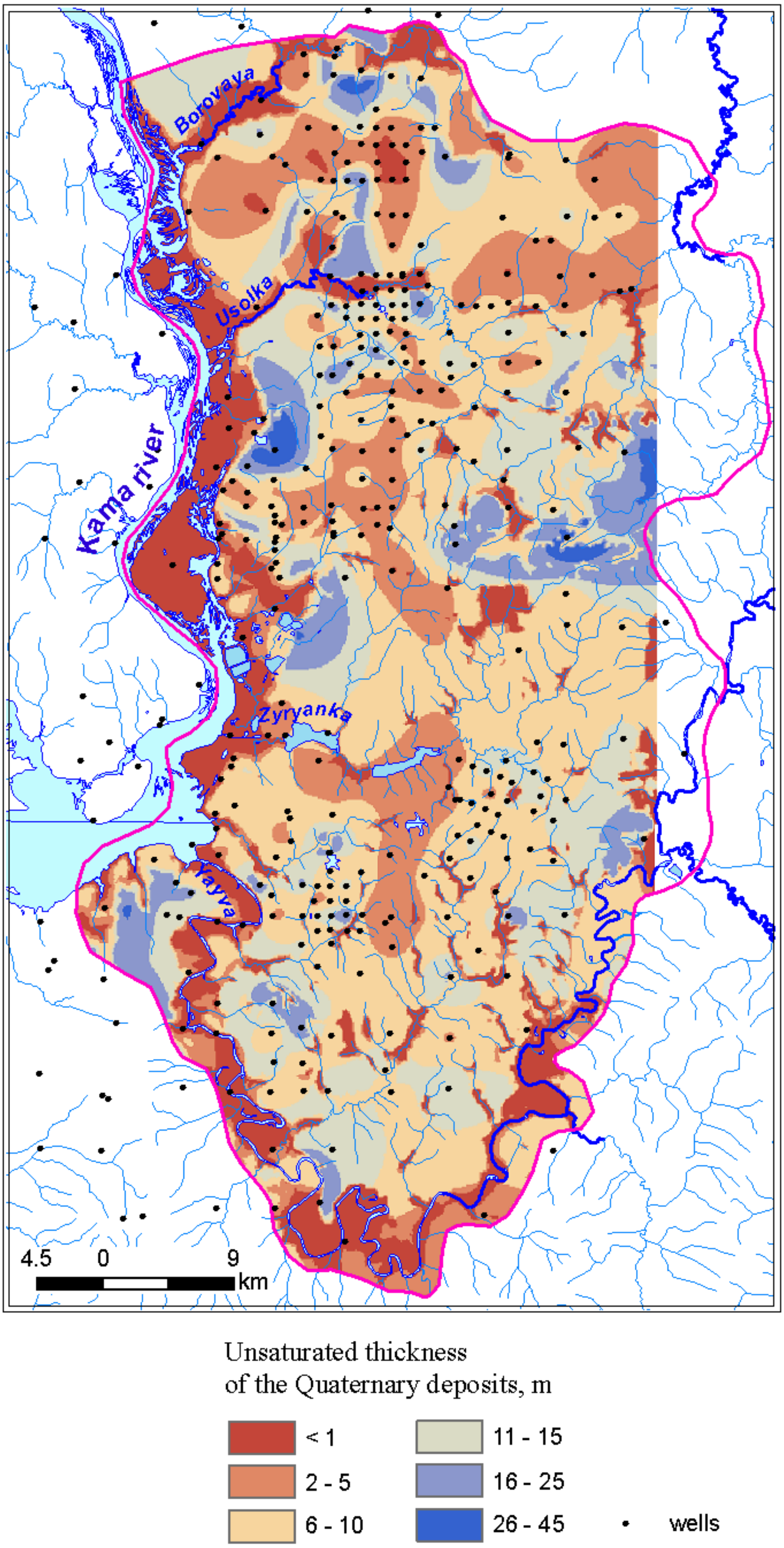


Figure 5.9. Map of thickness of the unsaturated part of the Quaternary deposits

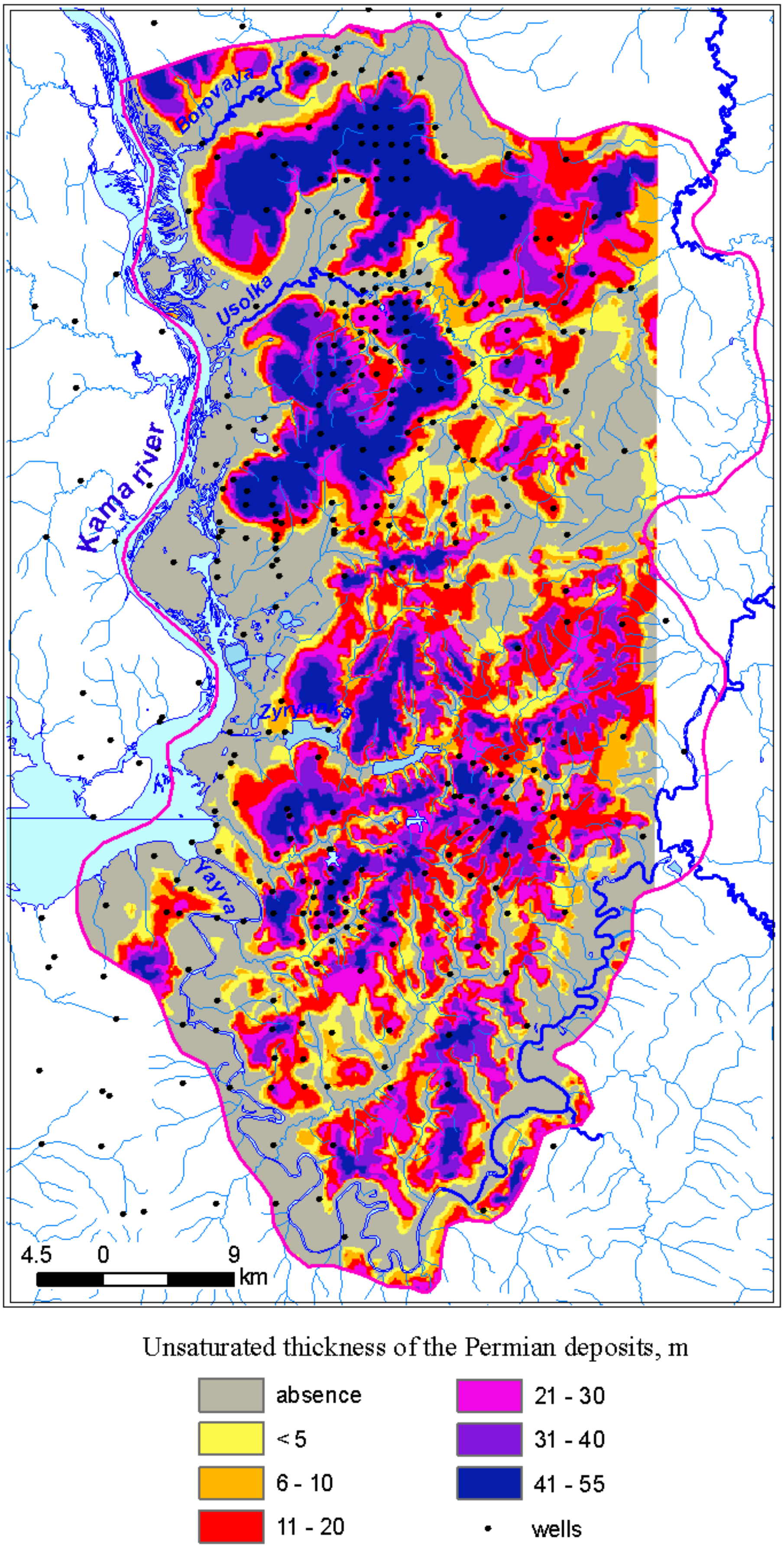


Figure 5.10. Map of thickness of the unsaturated part of the Permian deposits

Table 5.4. Characteristics of deposits of the upper layer (Quaternary) of the unsaturated zone

Type of the Quaternary deposits	Description	Rating SINTACS	Θ_s (average values)	Kf, m/day (average values)	n_{ef} (average values)
b IV - biogenic (90)	Peat (valley, transitional, high-moor). Thickness from 0.2 to 11 m Kf 0,1-1,64 m / day.	2 (peat)	4.5	0,7	0,34
a IV - alluvial deposits (100)	Alluvial deposits of floodplains. The large rivers (Kama Borovaya Usolka, Yaiva) are characterized by sandy and sandy-gravel type of section. Kf of floodplain sands 0.1-2.5 m / day. Gravel-pebble soils with sand and clay filler Kf 0.2-0.3 m /day.	6 (medium-fine alluvial)	0.25	2	0,24
a III tl-kd - alluvial deposits of I fluvial terrace	Gravel-pebble ground (mostly); sand, sandy loam, loam, clay, peat	6 (medium-fine alluvial)	0.25	2,5	0,24
a III tl+sg - alluvial deposits of II fluvial terrace	Sand, sandy loam, loam, clay	4 (medium-fine alluvial)	0.25	1,5	0,32
a II gr-el - alluvial deposits of III fluvial terrace	A high content of clay is characteristic for a section. Clay, layers of sand.	3 (medium-fine alluvial)	0.3	0,5	0,15
ds III vn - dealluvial deposits;	The composition of dealluvial deposits depends on the composition of rocks composing the upper part of the slope. In the north of the territory there are mainly sand, sandy loam with Kf 0,2-1,24 m /day, in the south - loam, clay. The average thickness of dealluvial deposits - 2-5 m	5 (sand complex) north; 2 (clay, silt) south	north 0,25 south 0,27	north 0,75 south 0,01	0,32 0,20
f II el - fluvioglacial sediments	Quartz sand: pulverescent, in some areas - argillaceous. Subordinate significance in a section have laminated loams. The average thickness from 3-17 m to 22 m Kf 0,63-5,33 m /day	6 (sand complex)	0,23	3	0,32
ed II –III - eluvial-deluvial deposits	Deposits displaced along the slope, thickness - 3 m. Section is similar to dealluvial (loam, clay, sand, sandy loam). In the north and central parts are mainly sand, sandy loam; the southern part - mostly clay ground.	5 (sand complex) – north 2 (clay, silt) south	north 0,25 south 0,27	north 0,75 south 0,01	0,32 0,20
e II-III - eluvial deposits	Unconsolidated products of weathering, topographically non-displaced. On the rocks of Solikamsk suites are presented by loamy-detritus material with thickness 1-1.5 m; on the clay rocks of sheshminskaya suite are presented by argillaceous material; on sandy rocks of sheshminskaya suite - sandy eluvium.	4	0,24	0,75	0,25
ad IV - alluvial-deluvial deposits	Like the a IV (alluvial deposits)	6 (medium-fine alluvial)	0,25	2	0,24
l IV - lake deposits	Clay, thin layers of peat.	2 (clay,peat)	0,3	0,001	0,1
g II lr - glacial deposits	Clay with inclusion of gravel, pebbles, detritus.	2 (medium-fine moraine)	0,3	0,001	0,1
t IV - technogenic deposits.	The composition is diverse. Clay-salt wastes.	4	0,27	0,05	0,15

Table 5.5. Characteristics of deposits of the lower layer of the unsaturated zone

Geological index	Description	Rating SINTACS	Θ_s (average values)	Kf, m/day (average values)	n_{ef} (average values)
N2ks Neogene. Pliocene. Kostanay suite.	Sand, gravel-pebble deposits with interlayers of clays.	6	0,23	2,5	0,32
P_1 ss Permian system. The upper series. Ufimsky stage. Sheshminskaya suite.	Rhythmic interbedding of argillites, siltstones with interlayers of sandstones and conglomerate lenses.	4	0,21	4	0,24
P_1 sl_2 Permian system. The upper series. Ufimsky stage. Solikamskaya suite. Terrigenous-carbonate stratum.	Interbedding of limestones, marls with clay, interlayer of siltstone, rarely sandstones.	5	0,12	7,5	0,14
P_1 sl1 Permian system. The upper series. Ufimsky stage. Solikamskaya suite. Salt-marl stratum.	Interbedding of dark-gray marls and clays with pyrite and gypsum inclusions, in the lower part - interlayering of gypsum and rock salt.	3	0,10	4	0,12

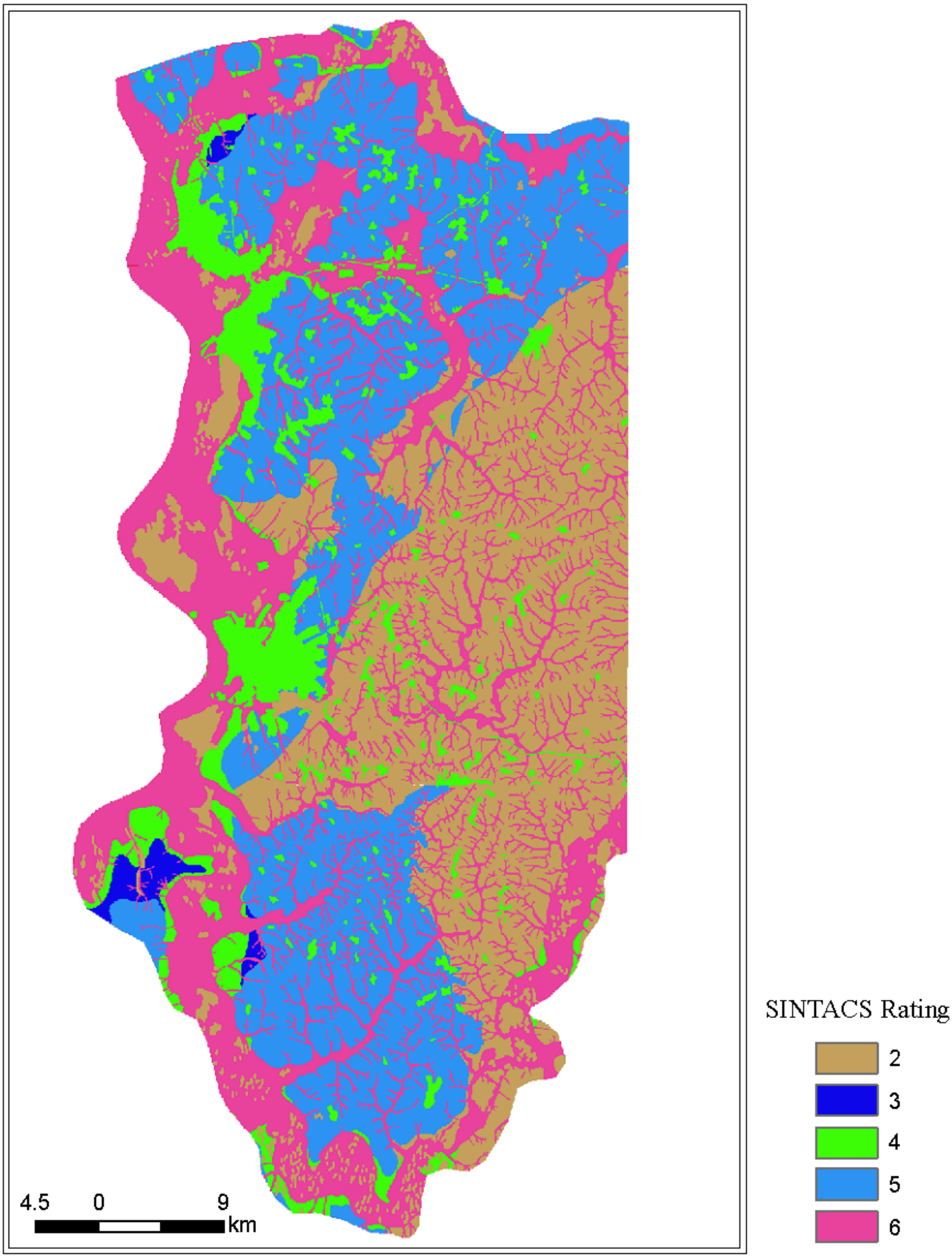


Figure 5.11. SINTACS rating for the upper layer (Quaternary deposits) of the unsaturated zone

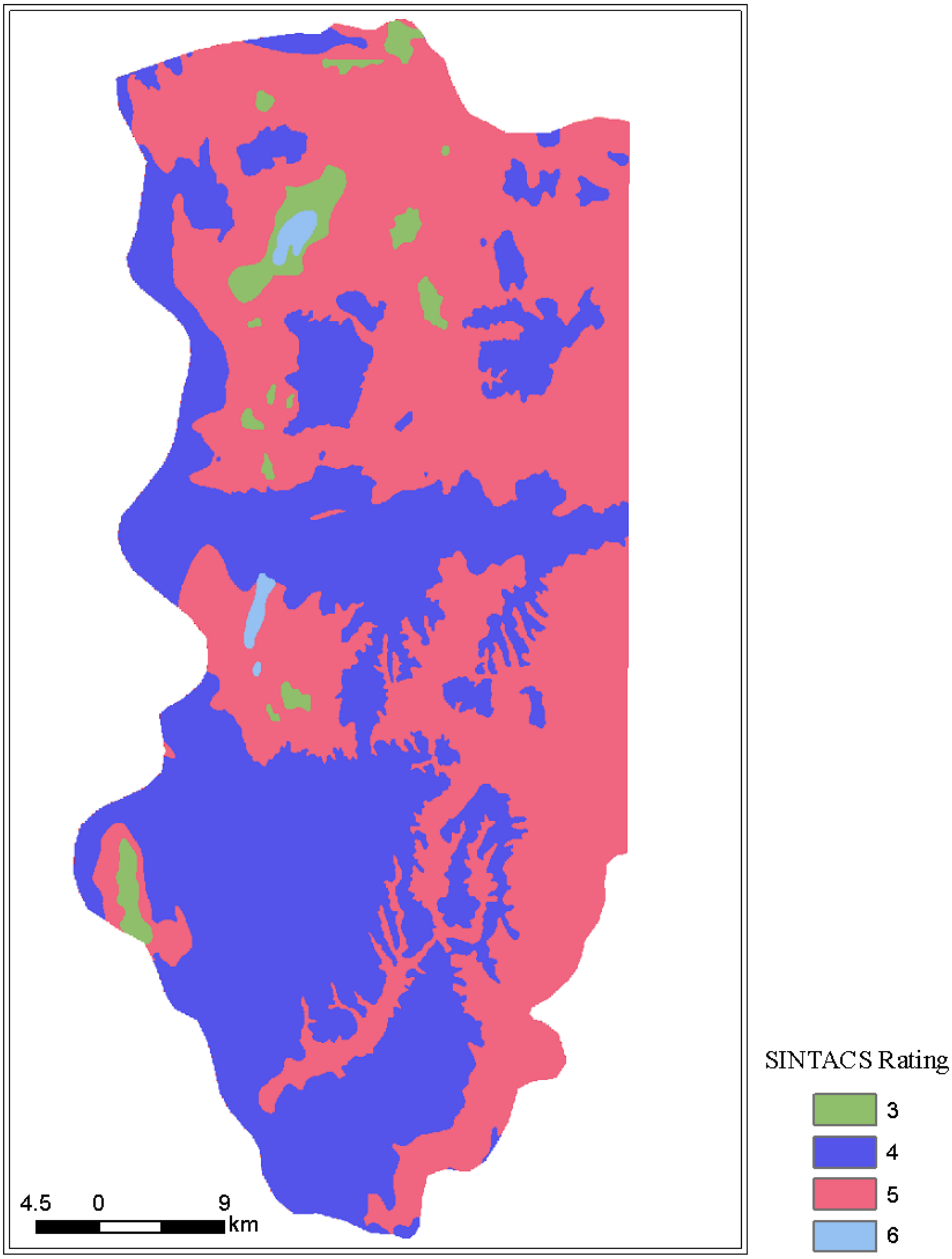


Figure 5.12. SINTACS rating for the lower layer (Permian deposits) of the unsaturated zone

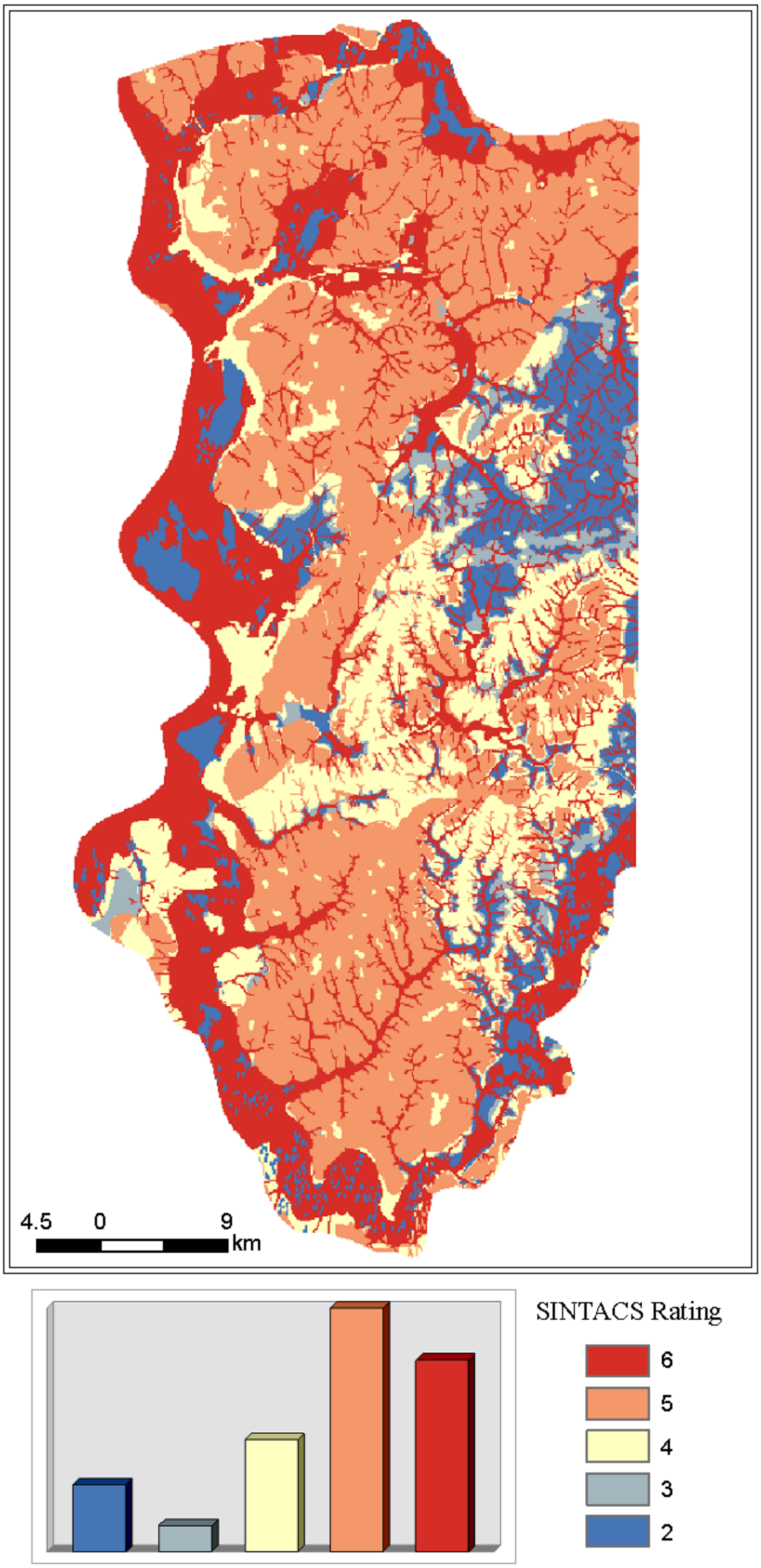


Figure 5.13. SINTACS rating for the unsaturated zone (parameter «N»)

T - Soil/overburden attenuation capacity

Table 5.6. Characteristics of soils

Types of soil	The predominant mechanical composition	Kachinsky	The Ferre triangle	SINTACS rating
Alluvial	Heavy loam	Heavy loam (40-50 % of clay)	clay loam	3
Sod-medium podzolic	Heavy loam	Heavy loam (40-50 % of clay)	clay loam	3
Sod-strongly podzolic	Heavy loam	Heavy loam (40-50 % of clay)	clay loam	3
Strongly podzolic	Medium loam	Medium loam (30-40 % of clay)	sandy clay loam	5
Soils of gullies, ravines, flood plains of small rivers and adjoining slopes	Loamy and sandy loam deposits	Medium loam (30-40 % of clay)	sandy clay loam	5
Medium podzolic	Sandy loam	Sandy loam (10-20 % of clay)	loamy sand	6

Figure 5.14. The Ferre triangle of soil

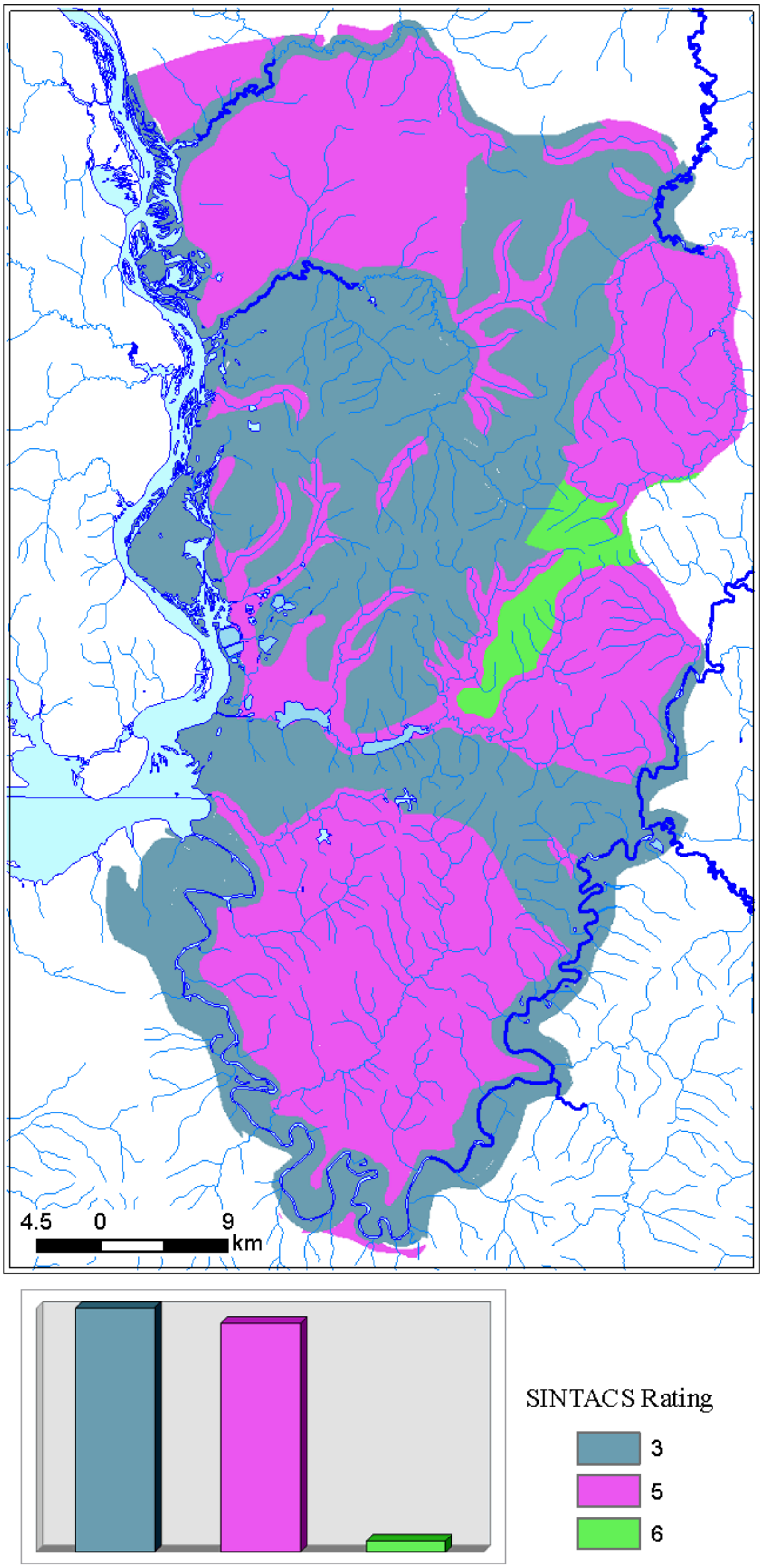


Figure 5.15. SINTACS rating for soil/overburden attenuation capacity

A - Hydrogeologic characteristics of the aquifer

Table 5.7. Characteristics of water-bearing rocks

Index	Description	K_f, m/day (average values)	K_f, cm/day (average values)	Rating SINTACS Acquifer charactersitics	Rating SINTACS Conductivity
a Q	Alluvial deposits of small rivers	0.5	7.87E-06	6 (medium-fine alluvial deposits)	4
a Q	Alluvial deposits of the rivers Kama, Yaiva	10	1.57E-04	8 (coarse alluvial deposits)	7
f Q el	Fluvioglacial deposits	2.5	3.94E-05	7 (sand complex)	5
P_1 ss	Sheshminsky deposits, argillaceous type with predominance of siltstones	0.5	7.87E-06	3 (Siltstone, sandstone)	4
P_1 ss P_1 sl_2	Sheshminsky deposits, argillaceous type Solikamsk deposits, marly-limestone deposits	5	7.87E-05	4 (sandstone) 4 (marle, limestone)	6
P_1 sl_2	Upper Solikamsk deposits, marly-limestone deposits	5	7.87E-05	5 (marle, limestone)	6
		10	1.57E-04	6 (fissured limestone)	7
P_1 sl_2	Upper Solikamsk deposits, marly-limestone deposits	20	3.15E-04	8 (fissured limestone)	7
		50	7.87E-04	8 (fissured limestone)	8
P_1 sl_1	Lower Solikamsk deposits	5	7.87E-05	4 (marle, limestone)	6

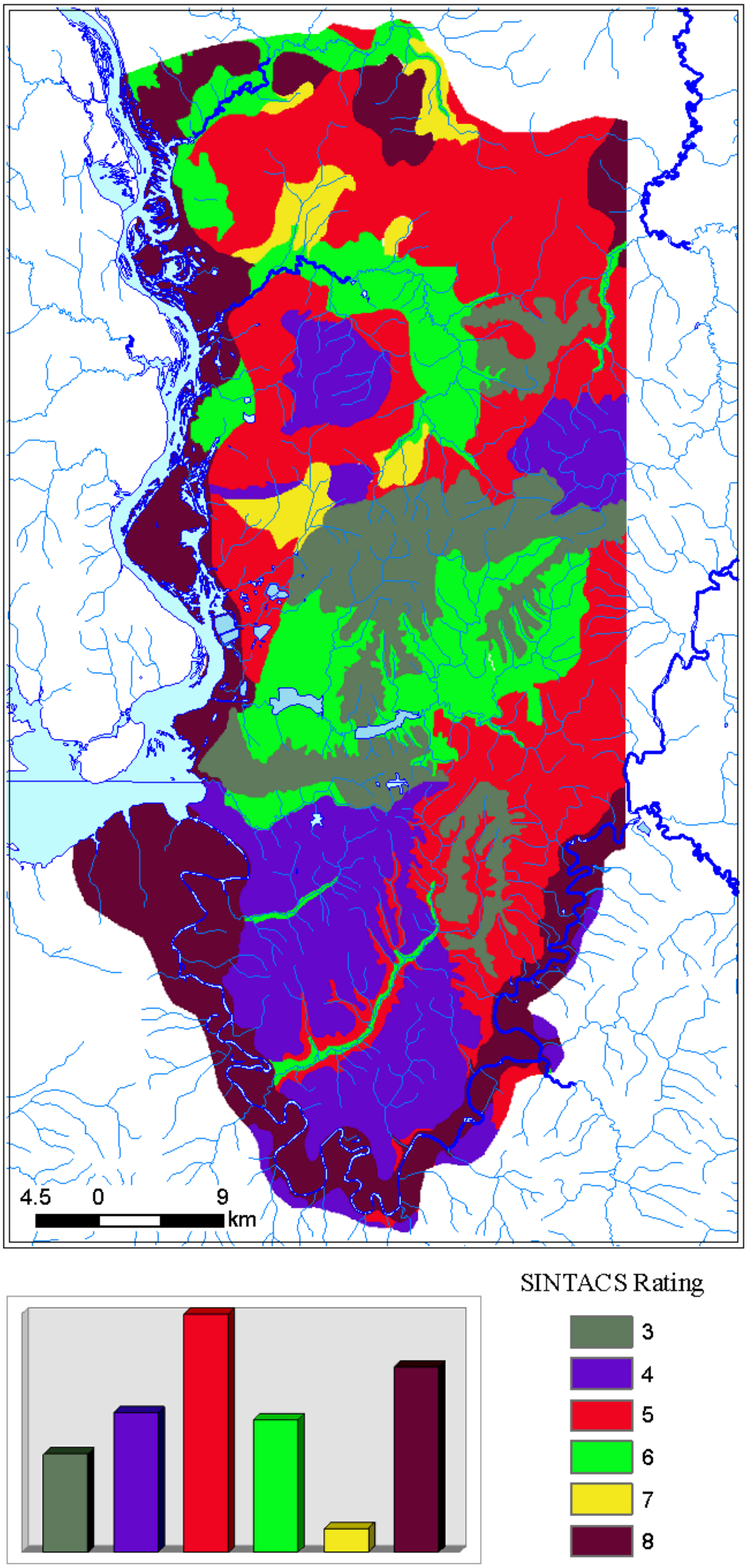


Figure 5.16. SINTACS rating for hydrogeologic characteristics of the aquifer

C - Hydraulic conductivity range of the aquifer

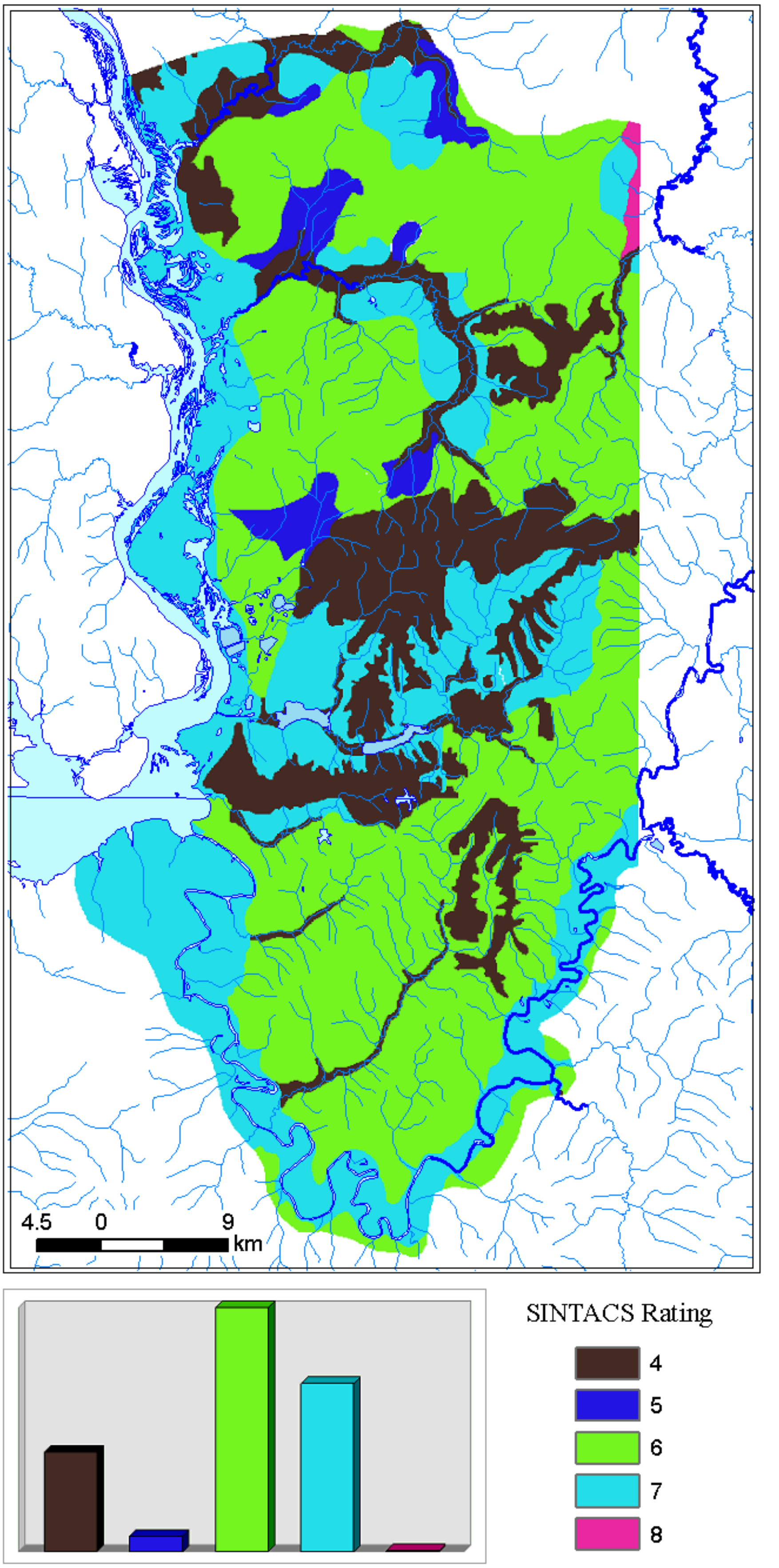


Figure 5.17. SINTACS rating for hydraulic conductivity of the aquifer

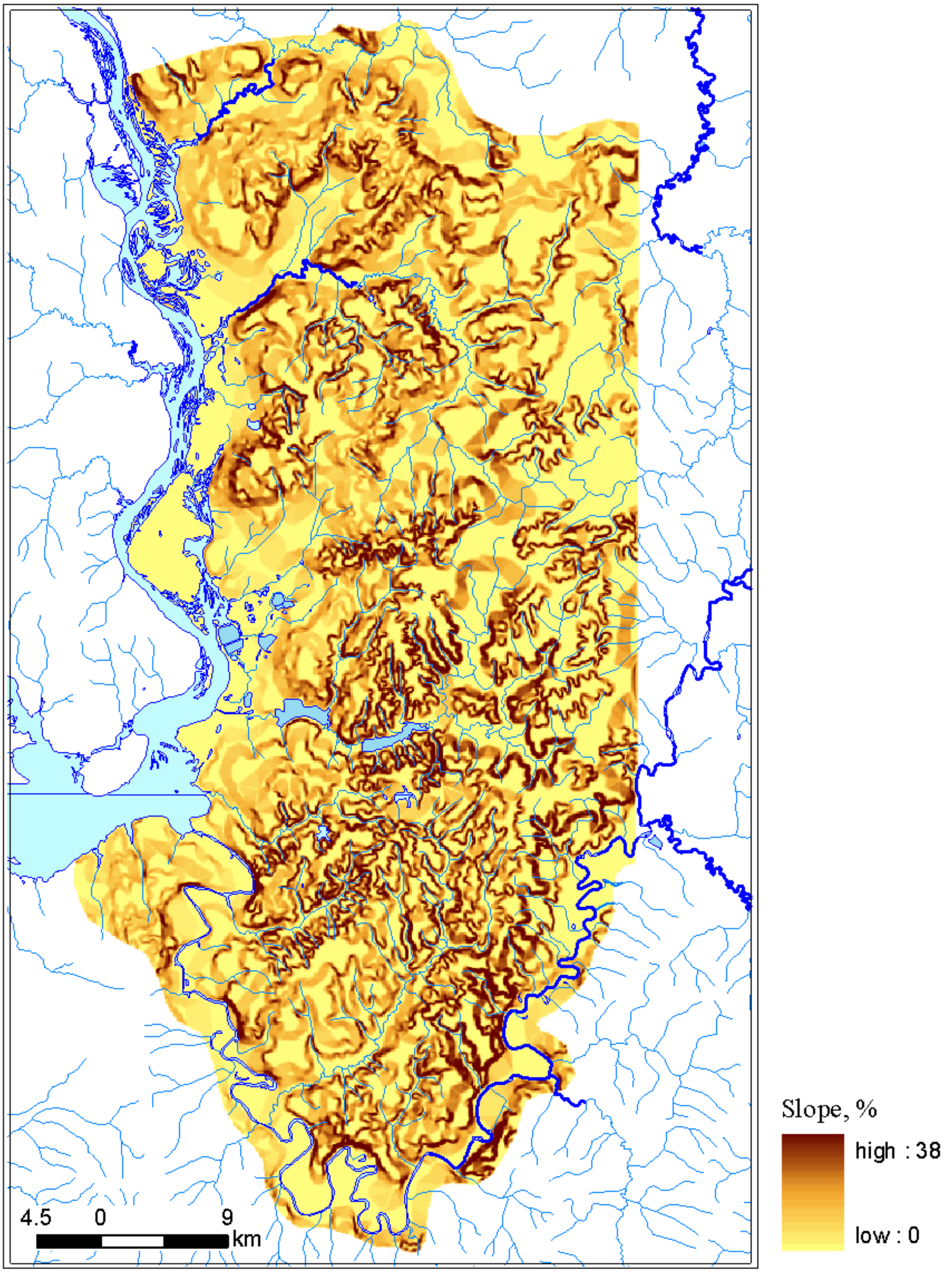
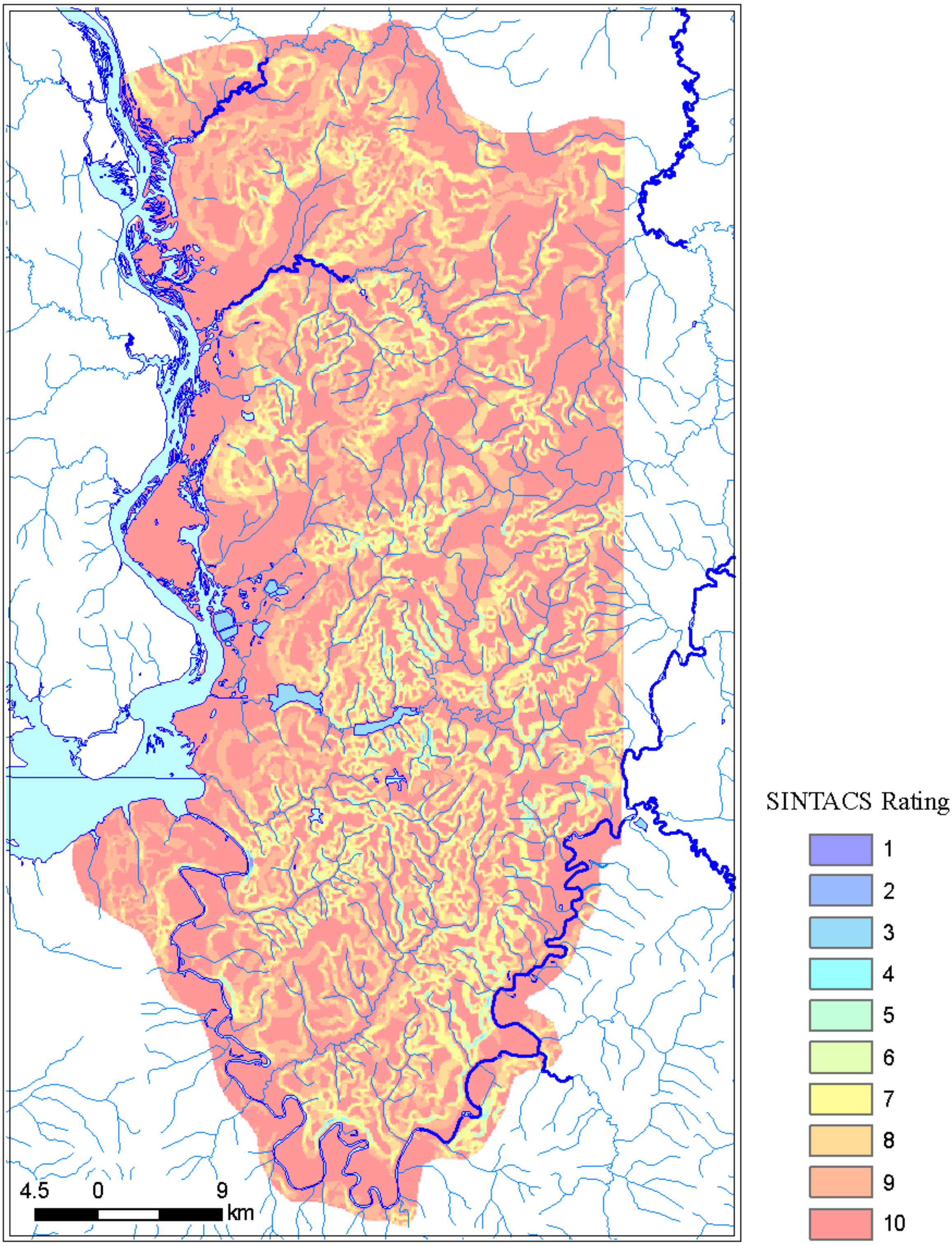


Figure 5.18. Slope of the territory, %



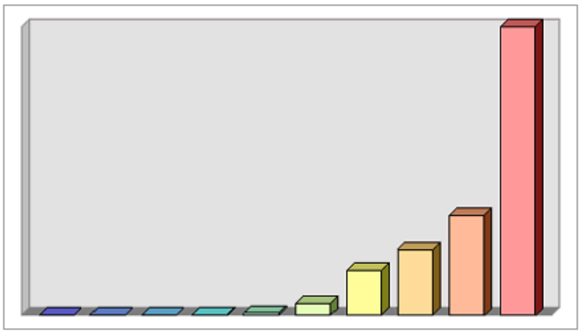


Figure 5.19. SINTACS rating for topographic slope

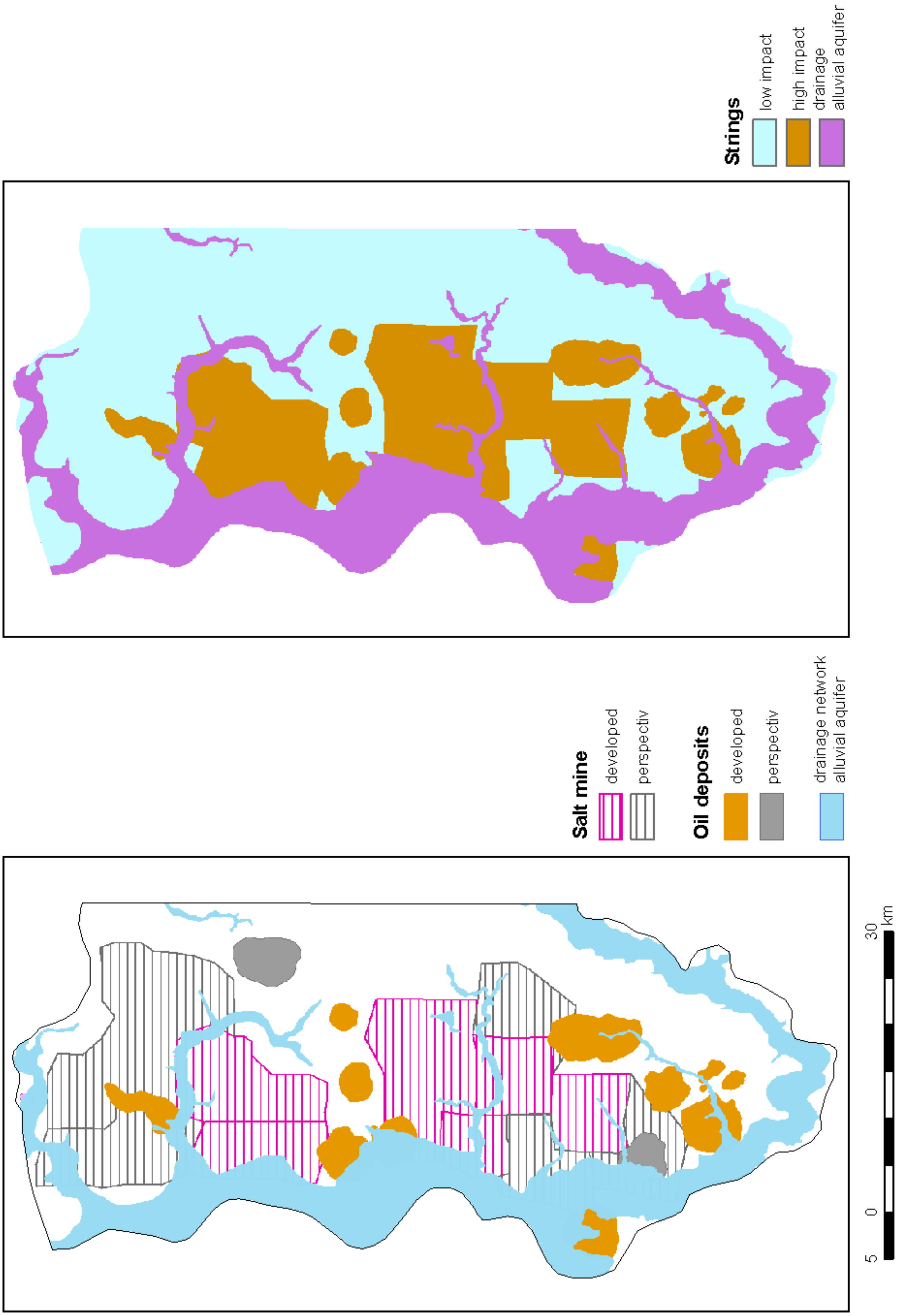


Figure 5.20. Hydrogeological and impact settings for SINTACS

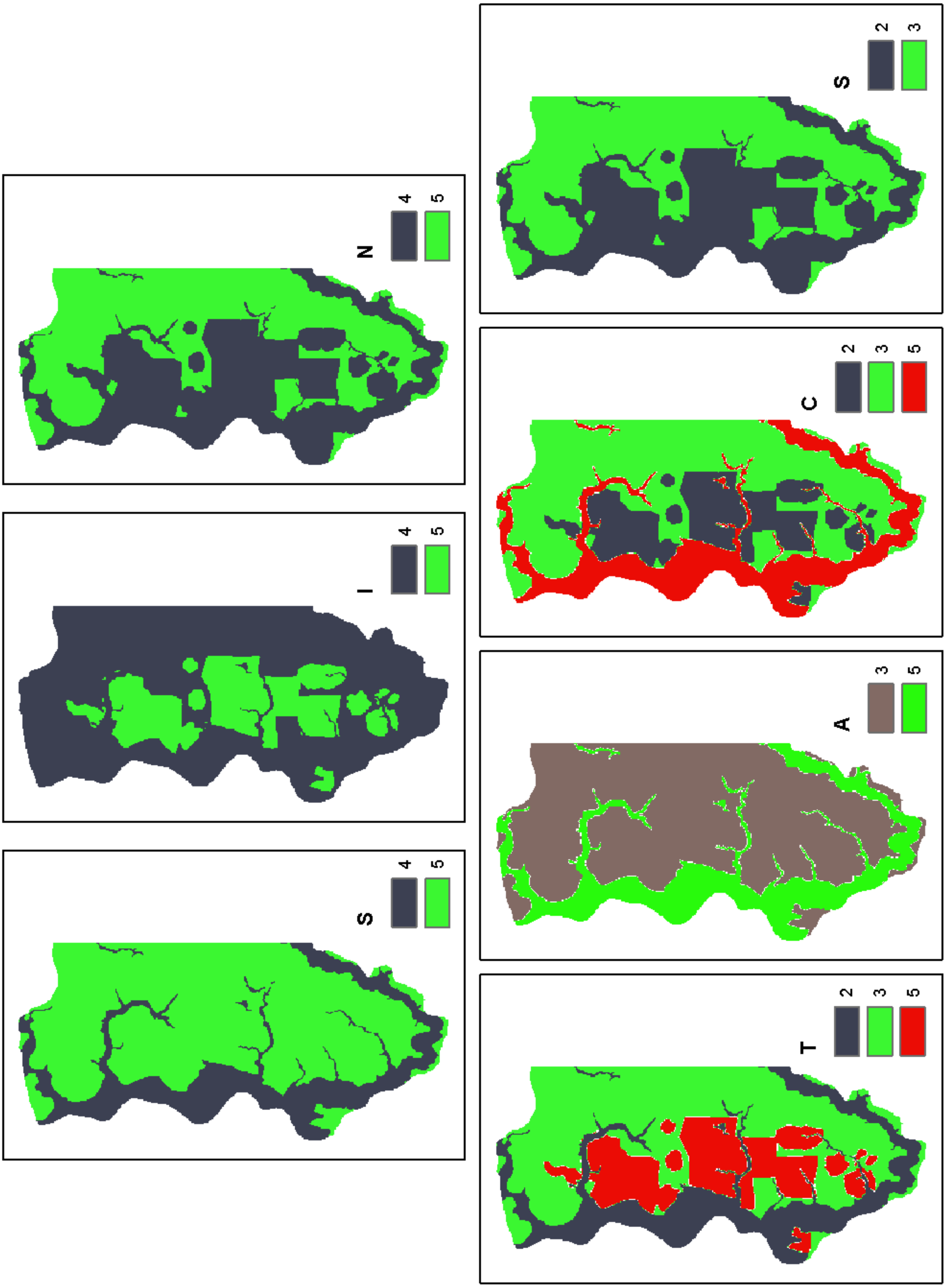


Figure 5.21. Strings of multiplier weights given for SINTACS

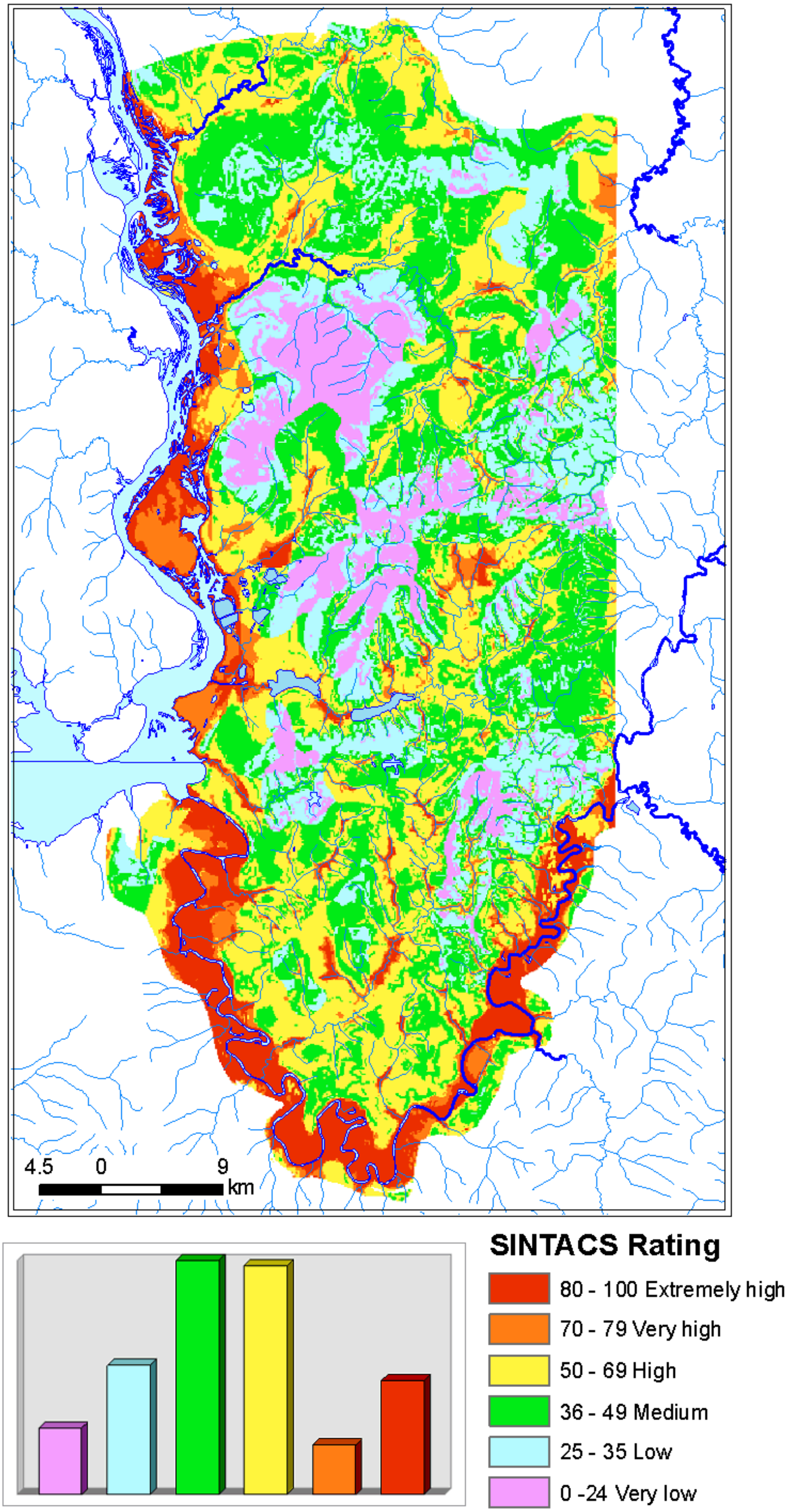


Figure 5.22. Intrinsic groundwater vulnerability map by SINTACS

5.2. Assessment of chloride ion travel time to the aquifer

Assessment of groundwater vulnerability to contaminants involved many researchers (Belousova, 2001, 2005, 2007, Pashkovskiy, 2002; Rogachevskaya, 2002; Zektser I.S., Karimova O.A. et al., 2004; Zao, 2005, Karimova, 2007; Akhmeteva et al., 2008). In these researches it is noted that vulnerability/protection of groundwater should be assessed to a particular pollutant.

In the observed territory the predominant source of groundwater pollution are chlorides. The pollutants come from two categories of sources: the technogenic brines filtered from the clay-salt sludge storages of the Upper Kama deposit of salts and loss of chloride brines when developing of oil deposits. Therefore, the conditions of groundwater vulnerability should be assessed in relation to the chloride ion.

Since the chlorides are not extremely hazardous chemical elements as a criterion for vulnerability assessment there was accepted the time required for the concentration of the pollutant carried by the infiltrating water to reach MAC on the upper boundary of groundwater (Belousova, 2001, 2007).

At the initial stage for assessing the intrinsic groundwater vulnerability to pollution is necessary to determine the seepage velocity of infiltration flow *v* (m/day) in the unsaturated zone.

To do this the equation of Bindeman (Bindeman, 1963) was used.

$$v = \frac{1}{\theta_s}\sqrt[3]{W^2 * K}, \quad (5.1)$$

где θ_s – saturated water content, fraction of unity; W – infiltration rate (effective infiltration) m/day; K – hydraulic conductivity (m/day).

The saturated water content θ_s was determined by the formula:

$$\theta_s = \frac{e \; * \; \rho_w}{\rho_s}, \quad (5.2)$$

where e – reduced porosity, ρ_w – density of water (g/cm^3); ρ_s – soils and rock-particle density (g/cm^3).

The coefficient of reduced porosity (e) is determined from the equation:

$$e = \frac{n}{1 - n}, \quad (5.3)$$

where n – porosity of the rocks, decimal fraction.

The data of density of grounds particles and the total porosity of grounds and rocks in the researched area determined from the results of physico-mechanical analysis (Baldin et al, 1998), as well as the calculated values of the saturated water content θs - are shown in Appendix 3. Averaged values of θs for different types of rocks are presented in Table. 5.4 (for the Quaternary deposits) and Table. 5.5 (for the Permian) and in Fig. 5.23, 5.24.

The calculations were performed for two variants: for the minimum value of the effective infiltration (Wmin) and for the maximum (Wmax). The values of the effective infiltration are shown in Fig. 4.5.

The values of hydraulic conductivity of the upper (Quaternary) and lower (Permian) layers of the unsaturated zone in the area of research are published in a report of Baldin et al. (Baldin et al, 1998), their average values are shown in Tables 5.4 and 5.5. Areal distribution of this parameter is shown in Fig. 5.25 and 5.26.

Determination of the seepage velocity of infiltration flow v (m/day) for the upper (Quaternary) layer of the unsaturated zone can be seen in Fig. 5.27 (for minimum values of infiltration) and Fig. 5.28 (for maximum values of infiltration). Accordingly, the values of the calculated parameter for the lower layer of the unsaturated zone, represented by Permian rocks, are shown in Fig. 5.29 and 5.30 for minimum and maximum values of infiltration.

In the case of infiltration (filtration) of brines, which density can reach 1.19-1.21g/cm^3 (TDS = 300-350 g/L), through the unsaturated zone there appears some additional gradient of filtration caused by a difference in the density of fresh water and brine - the gravitational gradient. The calculations of the gravitational gradient shows that it has a very small value, so the motion of brine through the unsaturated zone is not taken into account. The calculation of the gravitational gradient shows that it has a very small value, so it was not taken into account when calculating of the travel time of brines through the unsaturated zone.

As the transport model was considered the convective transport of chlorides without taking into account diffusion and hydraulic dispersion (piston displacement). As it is known, the chlorides are hardly sorbed by filtration medium and such model of its transfer meets the conditions of the fastest development of pollution process. In this case, the intensity of the transport of chloride can be estimated using the following equation (Bochever F.M., Lapshin N.N., Oradovskaya A.E., 1979):

$\overline{C}(x,t) = f(t_z - \lambda_k)$, (5.4)

where $\lambda_к = (H * n_{ef})/v$, H – depth of groundwater; v – seepage velocity of infiltration flow (m/day); n_{ef} – effective (active) porosity; $f(t_z - \lambda)$ – unit function, when $t_z < \lambda$, $f = 0$ and $C = 0$, when $t_z > \lambda$, $f = 1$ and $C = 1$.

$\overline{C}(x,t) = \dfrac{C - C_n}{C_p - C_n}$, (5.5)

where C – the desired concentration of Chloride ion in groundwater, g/L; C_n – the initial concentration of chloride ion in the rocks, g/L; C_p – concentration of chlorides in the technogenic (anthropogenic) brines, g/L.

The main criterion of assessing the natural groundwater vulnerability to pollution by chlorides is the time during which their concentration in groundwater reaches the values of maximum allowable concentration (MAC). MAC for chlorides in Europe is 0.25 g/L, in Russia - 0.35 g/L.

Equation (5.4) relatively the time during of which the concentration of chlorides reaches MAC - t_{MAC} (in fact, the time during of which the brine from the earth surface reaches the groundwater level) is as follows:

$$t_{\mathrm{MAC}} = \frac{Hn_{\mathrm{ef}}}{v}. \quad (5.6)$$

where H – depth of groundwater; v – seepage velocity of infiltration flow, m/day; n_{ef} – effective (active) porosity.

The values of effective porosity of the upper and lower layer were taken from the referenced data (McWhorter D., Sunada D.K., 1977). Their values are given in Table. 5.4 and 5.5, as well as in Fig. 5.31 and 5.32.

The calculations of the time of brines filtration were performed separately for the upper and lower layer of unsaturated zone. In this case, H in formula (5.6) reflects the thickness of the Quaternary deposits in the unsaturated zone (see Figure 5.9) and the Permian deposits in the unsaturated zone (see Figure 5.10). The total time of travel of brines through the unsaturated zone is obtained by summing the results calculated for the upper and lower layer.

The total time of brines filtration to the groundwater level (t_{MAC}) is shown on two maps, constructed for the case of the minimum infiltration (Figure 5.33) and for the case of the maximum infiltration (Figure 5.34). These maps reflect the quantitative assessment of groundwater vulnerability in the investigated area in relation to chlorides.

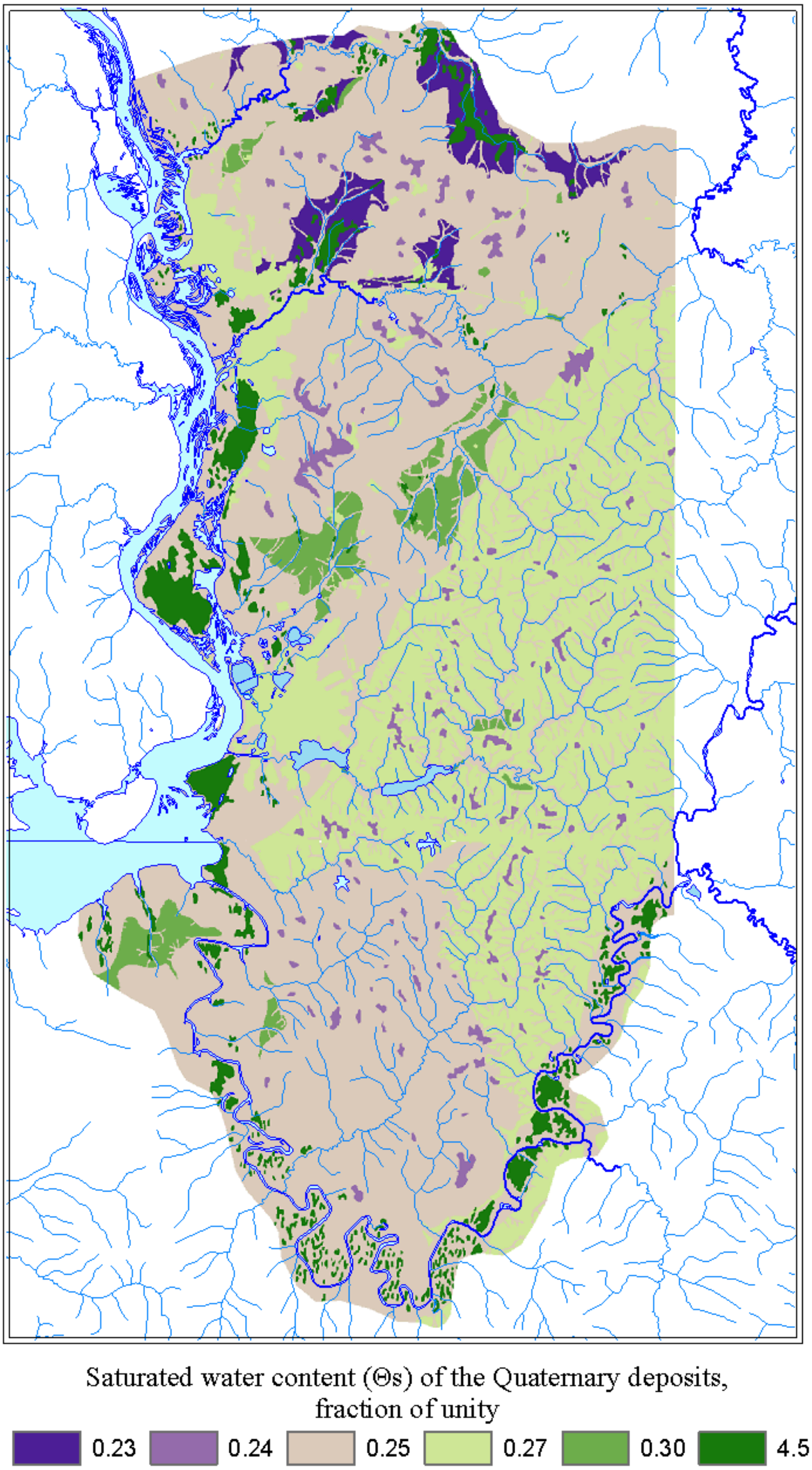


Figure 5.23. Average values of saturated water content (Θs) of the Quaternary deposits

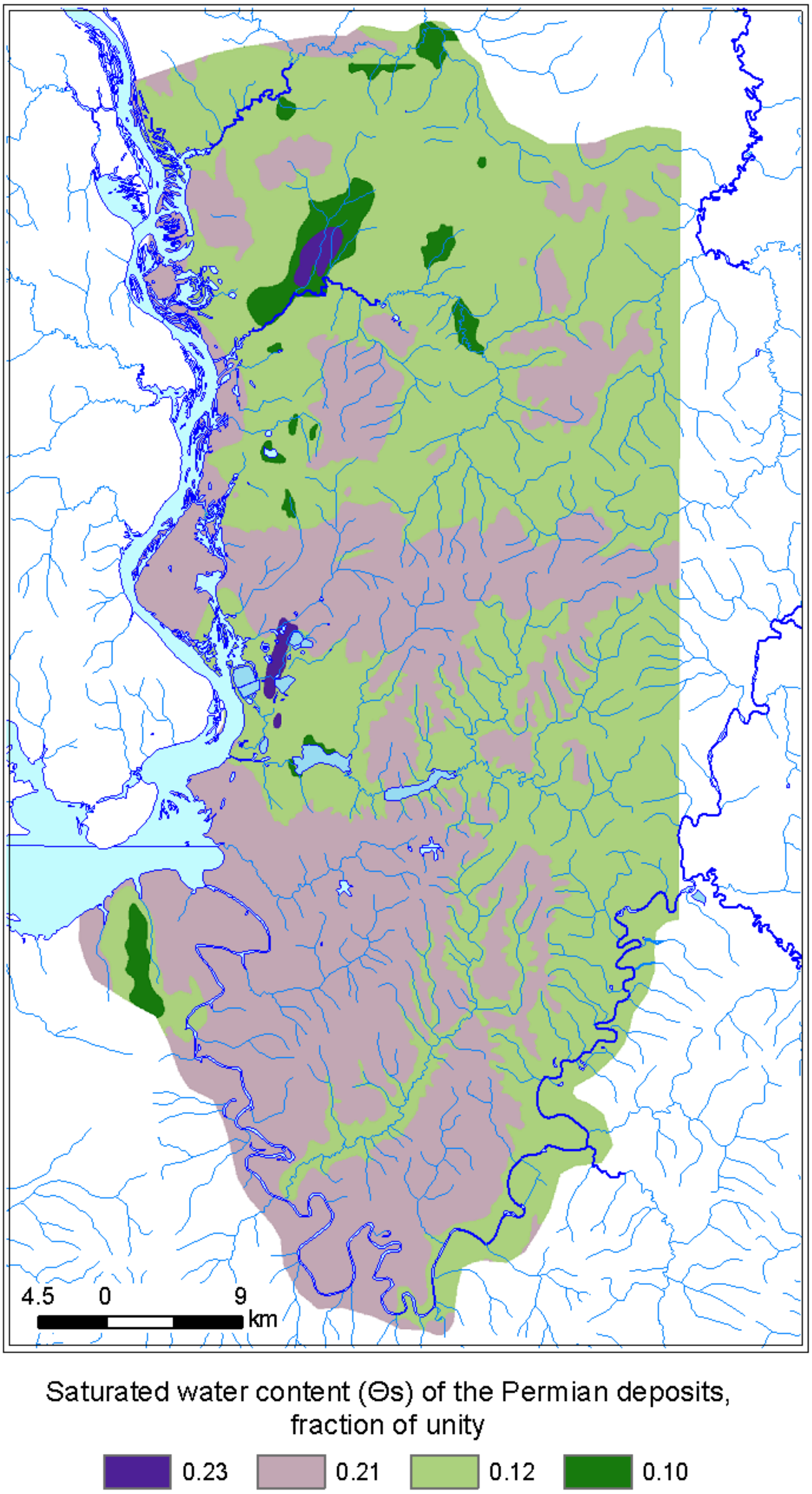


Figure 5.24. Average values of saturated water content (Θs) of the Permian deposits

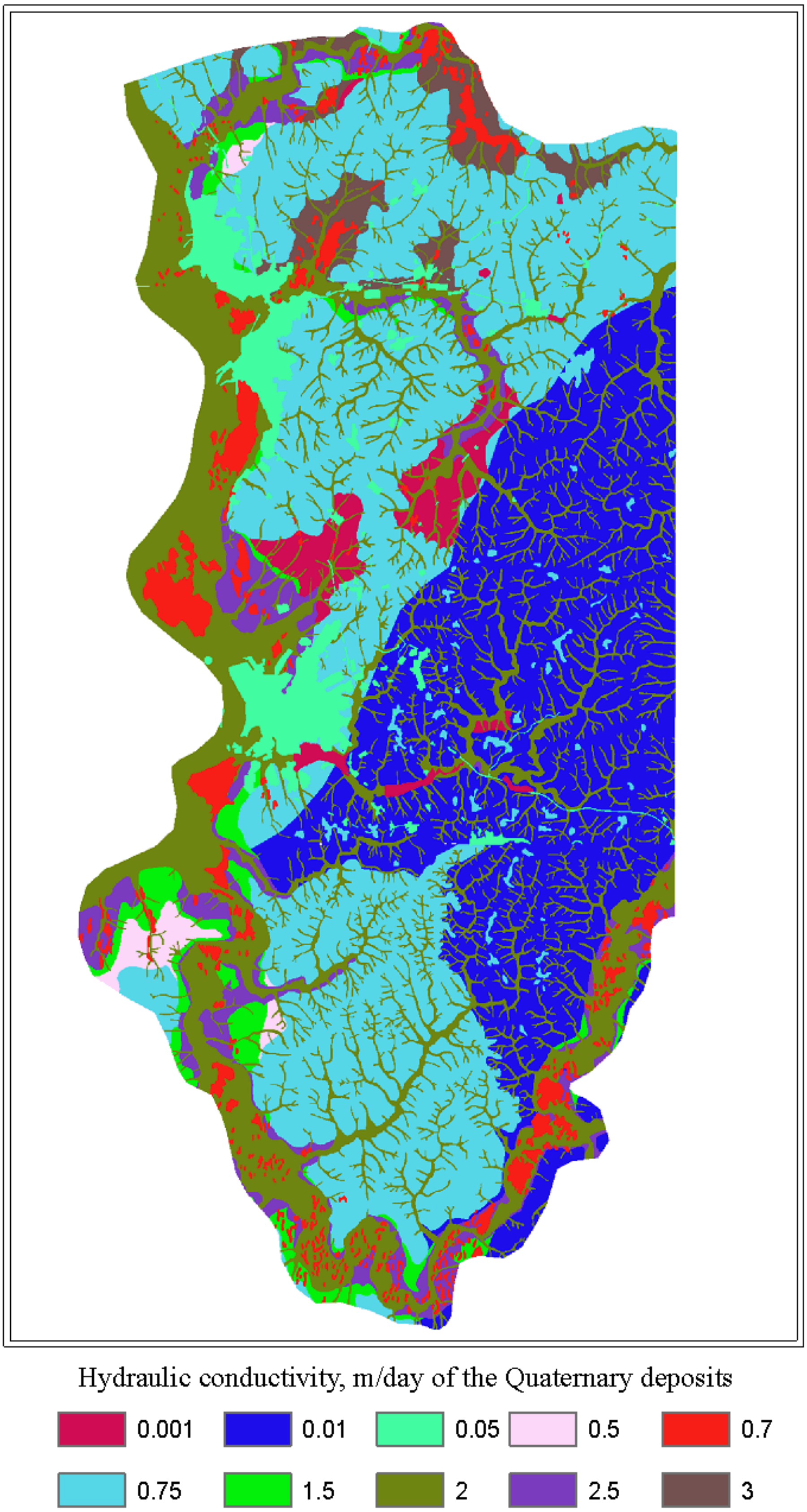


Figure 5.25. Average hydraulic conductivity values of the Quaternary deposits

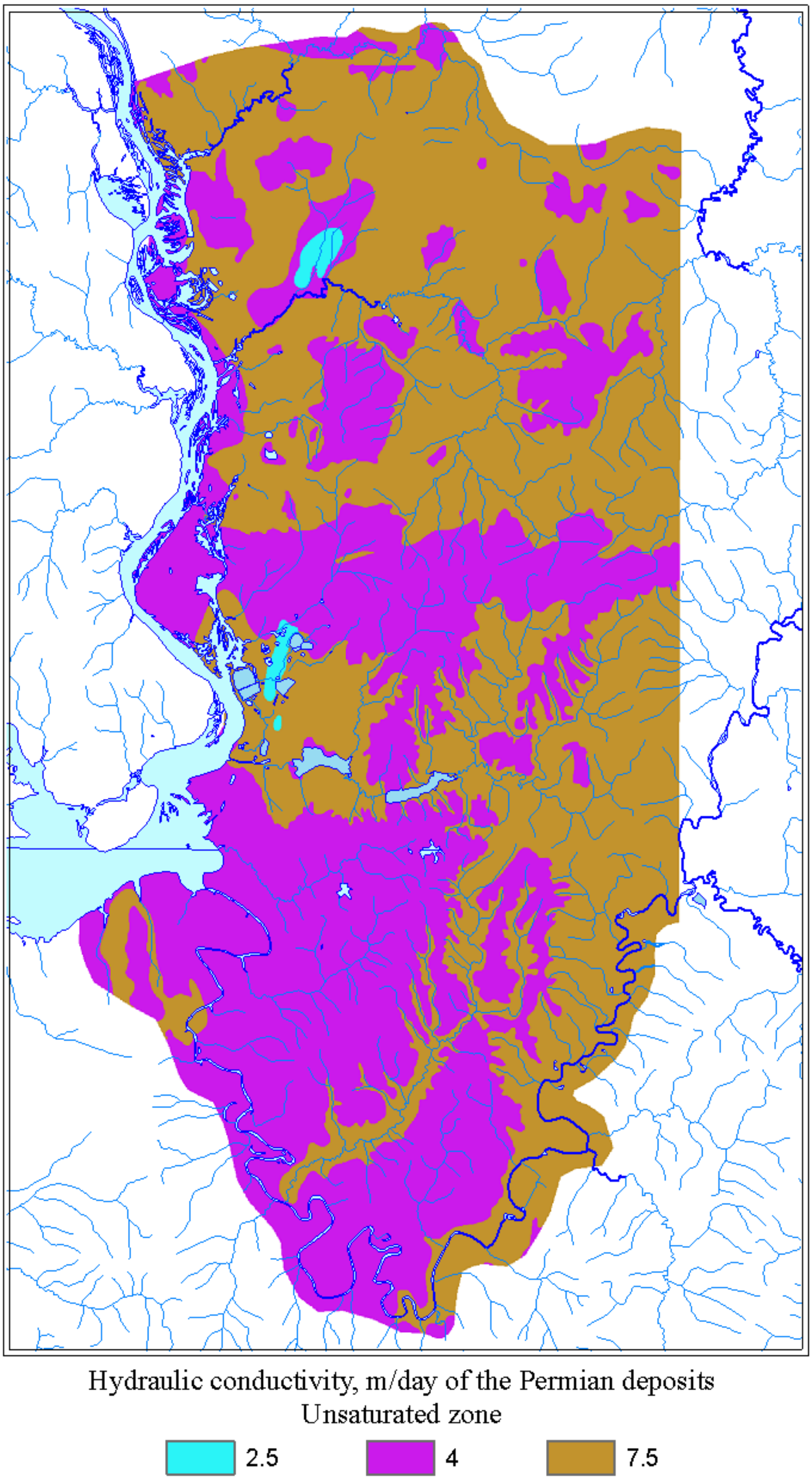
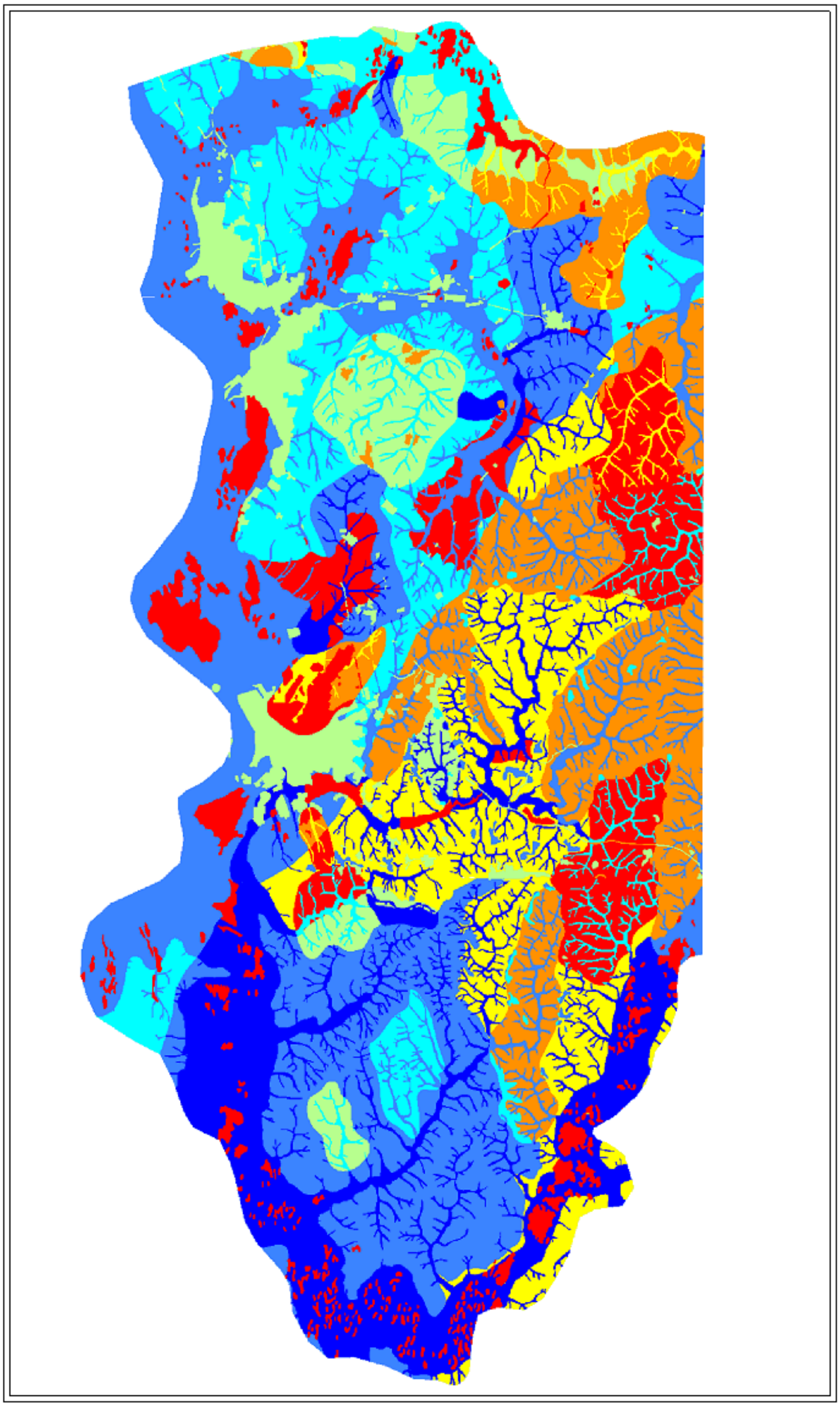


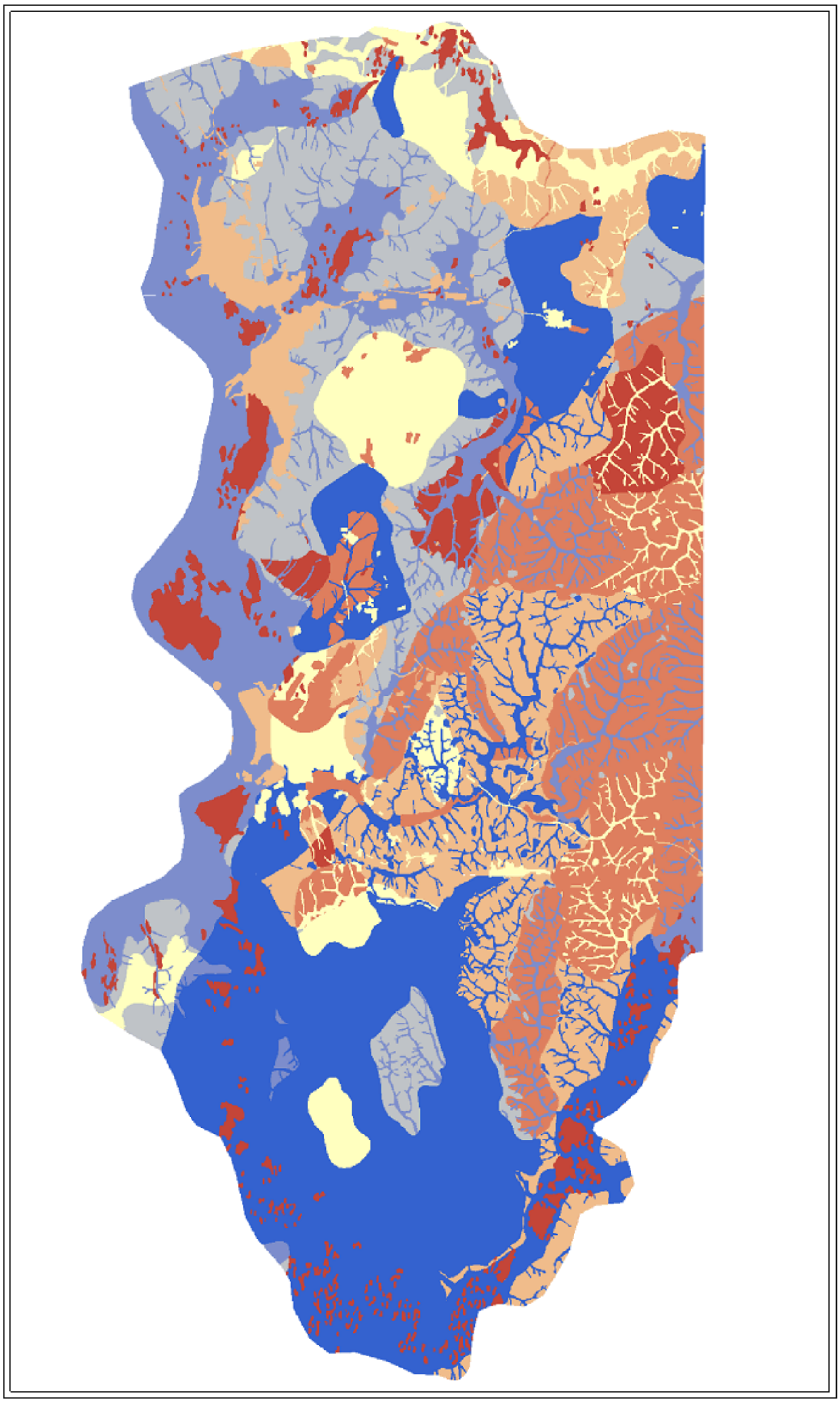
Figure 5.26. Average hydraulic conductivity values of the Permian deposits (unsaturated zone)



Seepage velocity of infiltration flow, m/day. Minimum infiltration rate (Wmin)
Quaternary deposits

0.0001 - 0.001
0.0011 - 0.002
0.002 - 0.0025
0.0026 - 0.005
0.0051 - 0.008
0.0081 - 0.0125
0.0126 - 0.03

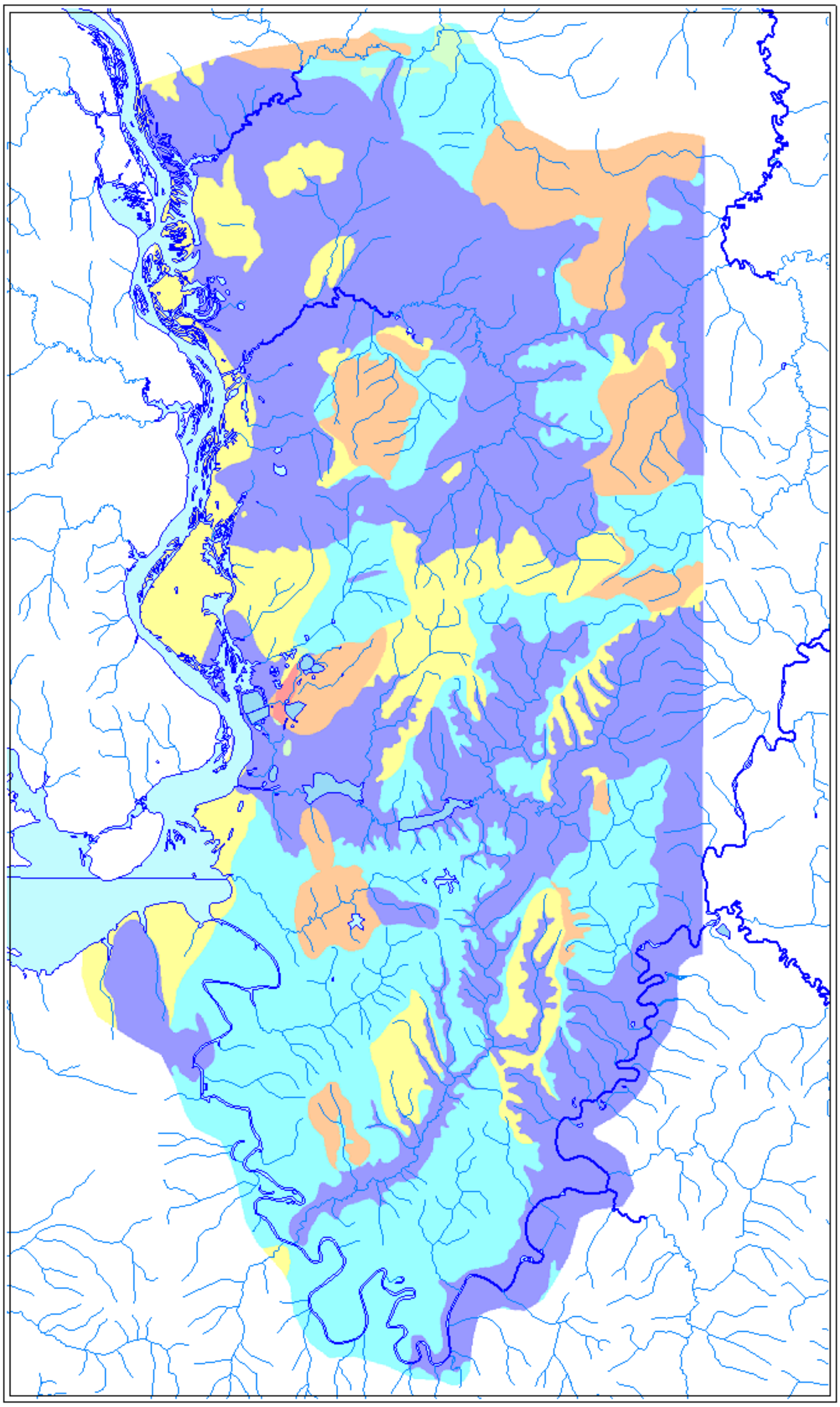
Figure 5.27. Seepage velocity of infiltration flow for the minimum infiltration rate (Quaternary deposits)



Seepage velocity of infiltration flow, m/day. Maximum infiltration rate (Wmax)
Quaternary deposits

0.0002 - 0.0015
0.0016 - 0.003
0.003 - 0.005
0.0051 - 0.01
0.01 - 0.015
0.015 - 0.02
0.02 - 0.05

Figure 5.28. Seepage velocity of infiltration flow for the maximum infiltration rate (Quaternary deposits)



Seepage velocity of infiltration flow, m/day. Minimum infiltration rate (Wmin)
Permian deposits

0.0025 - 0.03	0.003 - 0.01	0.001 - 0.015
0.015 - 0.02	0.02 - 0.025	0.025 - 0.03
	0.03 - 0.1	

Figure 5.29. Seepage velocity of infiltration flow for the minimum infiltration rate (Permian deposits)

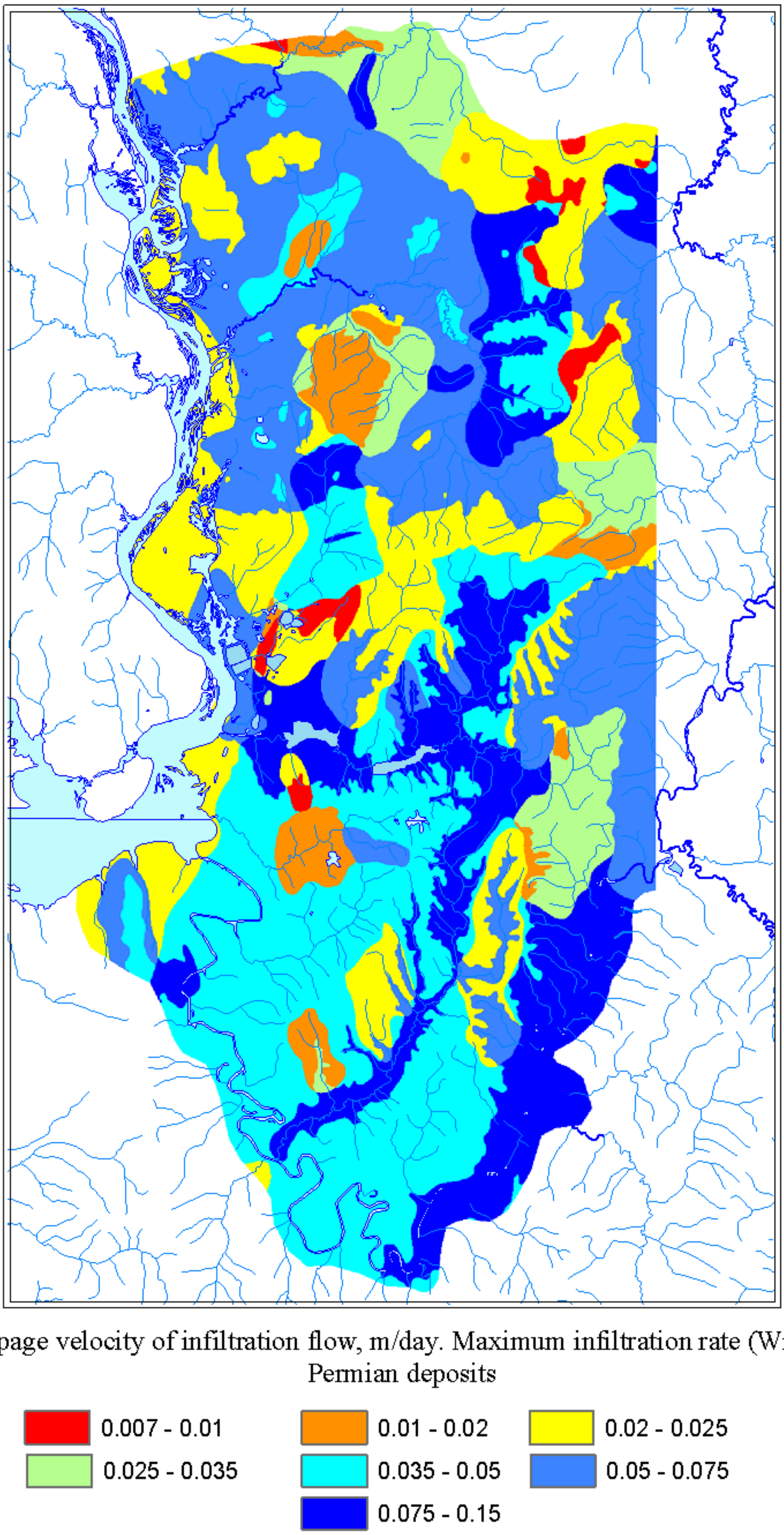


Figure 5.30. Seepage velocity of infiltration flow for the maximum infiltration rate (Permian deposits)

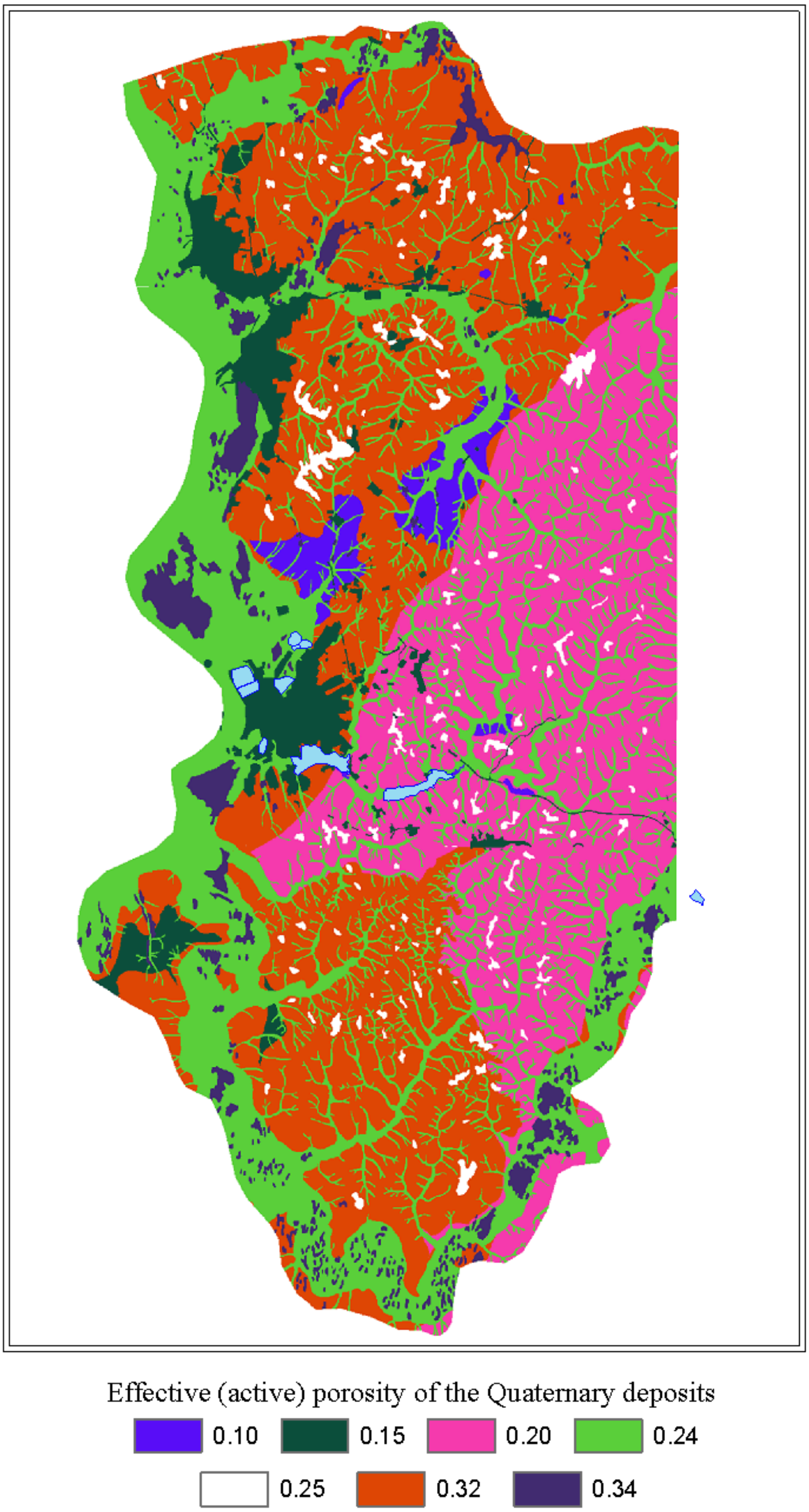
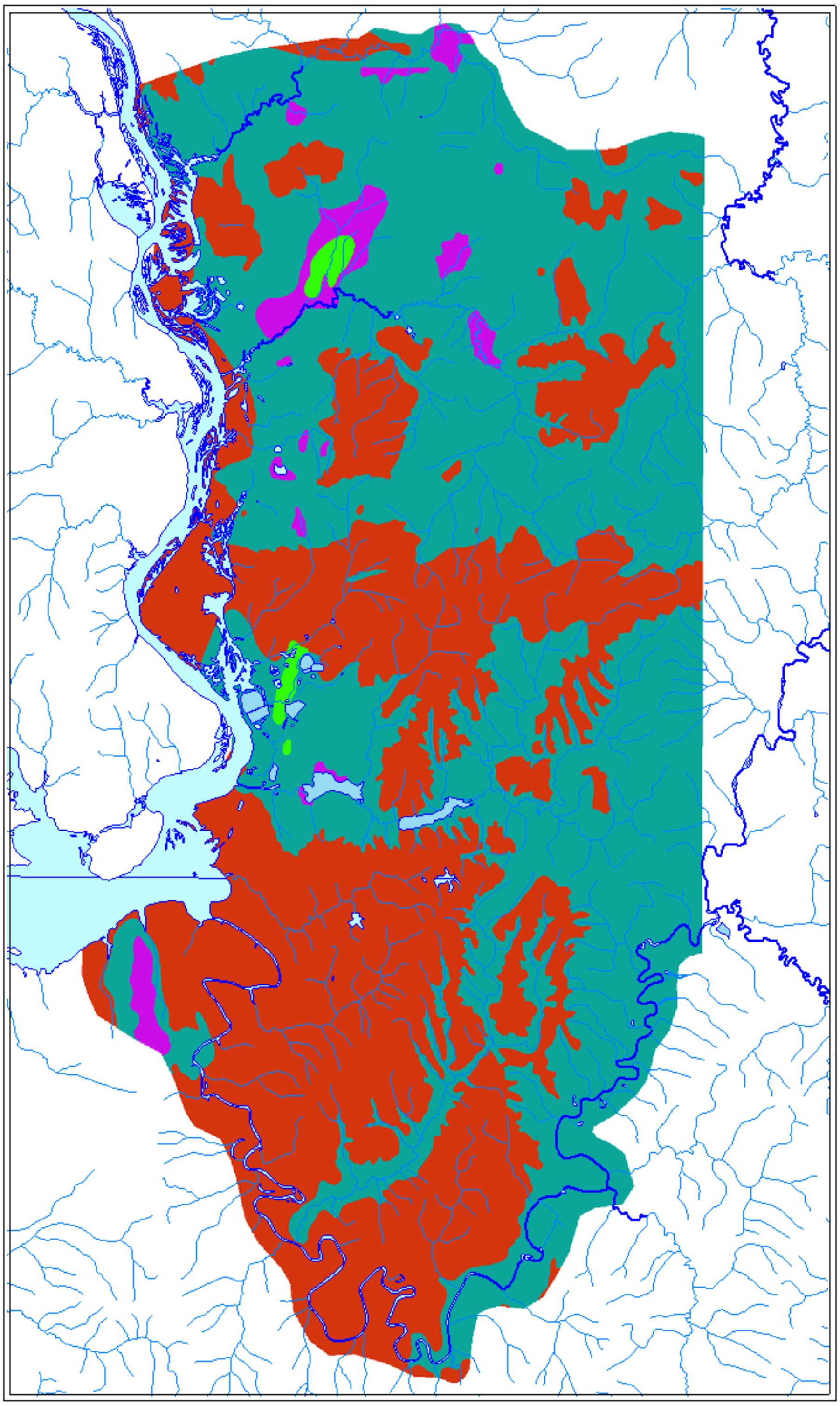


Figure 5.31. Average values of effective (active) porosity of the Quaternary deposits



Effective (active) porosity of the Permian deposits

0.12 0.14 0.24 0.32

Figure 5.32. Average values of effective (active) porosity of the Permian deposits

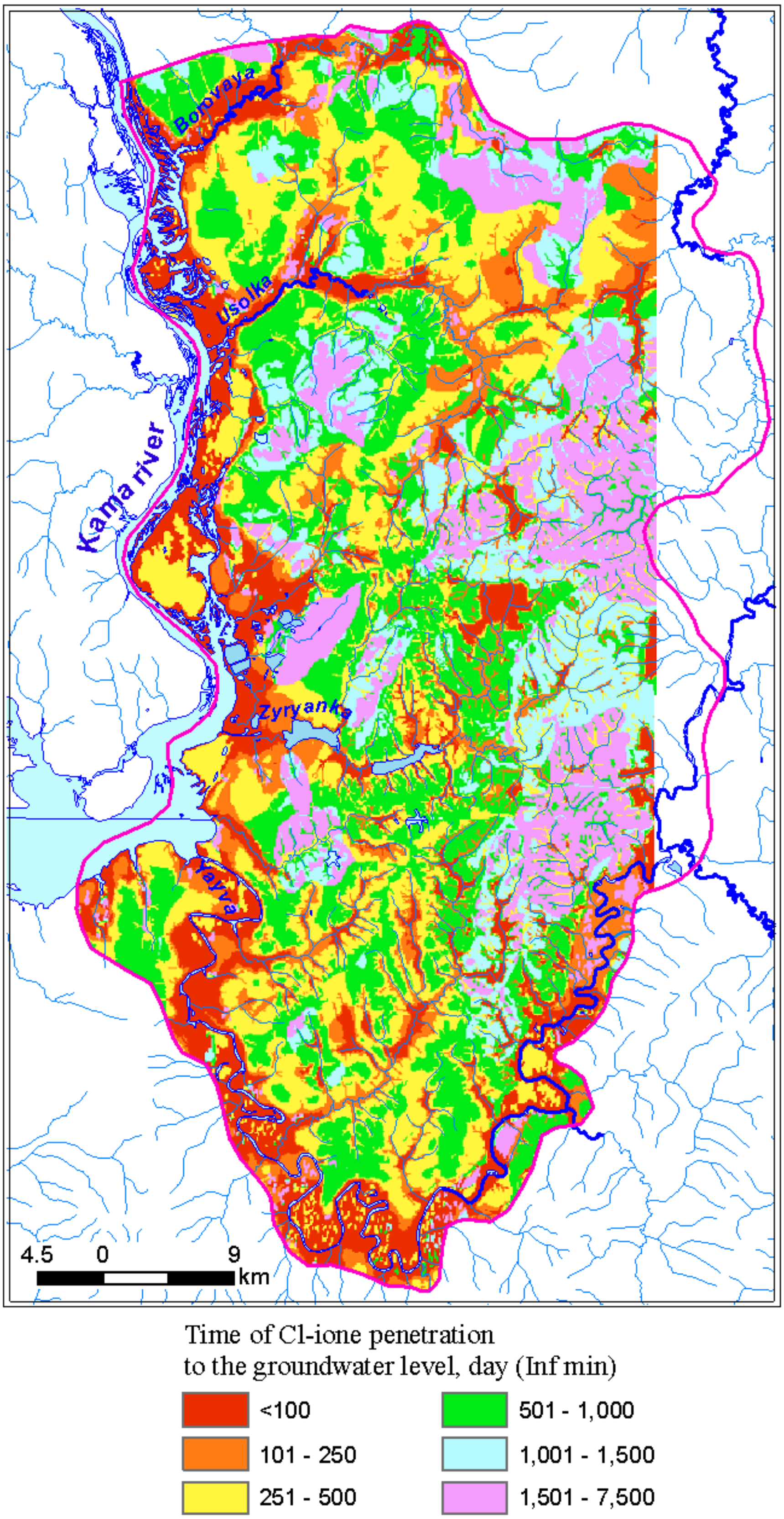


Figure 5.33. Time of Cl-ion penetration to the groundwater level for the minimum infiltration rate

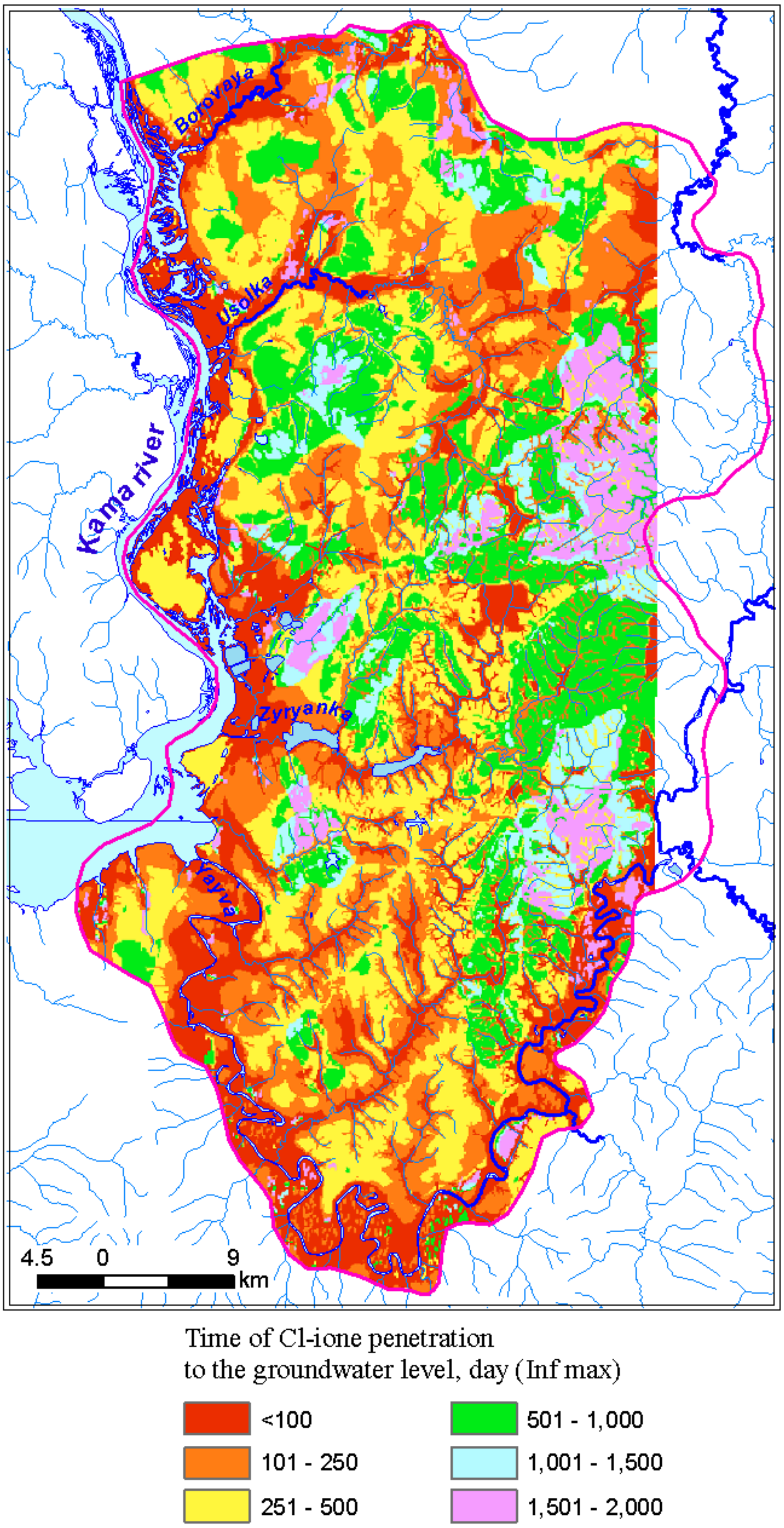


Figure 5.34. Time of Cl-ion penetration to the groundwater level for the maximum infiltration rate

5.3 Results of researches and their analysis

The resulting maps showing the vulnerability assessment of groundwater by two methods are shown in Fig. 5.22 (SINTACS) and Fig. 5.33 and 5.34 (calculation of chlorides travel time).

As is evident in Fig. 5.22 groundwater with «Medium» and «High» degree of vulnerability are predominate on the investigated area. In comparison, the areas with groundwater of «Extremely high» and «Low» vulnerability are occupied approximately in 2 times smaller territory.

The most vulnerable areas with «High» and «Extremely high» degree of vulnerability are almost completely located in the valley of the Kama river and in the valley of its largest, in this territory, tributary - r. Yaiva (see also Fig. 5.22). The valleys of these rivers formed in the Paleogene are characterized by minimum depth of groundwater and higher, in comparison with other rivers, filtration characteristics of alluvium. Overall, the assessment of groundwater vulnerability made by method SINTACS can be judged by the statistical analysis performed by a tool of ArcGIS «Zonal Statistics» (Table 5.8). In the Table 5.8, in the column «Index of the aquifer» there is the designation of the aquifer (see also Figure 4.1), and in the column «Area» there is the area of its distribution within the territory under research in km^2. In the column «Mean» of the table there are the average values of the normalized estimates of SINTACS (or the average values of index SINTACS for each aquifer), and in the column «Degree of vulnerability» there are the degree of vulnerability corresponding to these values according to SINTACS.

Table 5.8. The mean vulnerability index SINTACS calculated for aquifer in the studied area

Index of the aquifer	Area, km^2	Vulnerability index SINTACS				
		Min	Max	Mean	Degree of vulnerability	STD
f Qel	70.2	24	93	54	high	12
aQ	642.0	11	100	75	very high	16
P_1 ss	1016.2	0	100	41	medium	13
P_1 sl_2	788.2	7	98	43	medium	16
P_1 sl_1	14.5	18	68	38	medium	10

f Qel - Water permeable, locally water bearing Elovsky fluvioglacial horizon; **aQ** -Water-bearing, locally poorly productive water-bearing Quaternary alluvial horizon; **P_1ss** - Poorly productive water-bearing locally water bearing Sheshminsky terrigenous complex; **P_1sl_2** - Water-bearing upper Solikamskaya terrigenous-carbonate subsuite; **P_1sl_1** - Poorly productive water-bearing lower Solikamskaya salt-marl subsuite

As shown in the Table 5.8, besides the alluvial aquifer with very high degree of vulnerability, the locally spread fluvioglacial horizon is also distinguished by high degree of vulnerability. Aquifers in Sheshminskiy and Solikamsky deposits have mainly medium vulnerability.

Analogous statistical calculations were performed for sites with different amount of natural groundwater resources (see also Fig. 4.4). The sites with natural resources from1 to 2 and from 2 to 5 l/s·km^2 occupy the most part of the investigated area (Table 5.9) and, correspondingly, are characterized by medium and high degree of vulnerability in SINTACS (degrees of vulnerability were determined by the mean value). The sites with natural groundwater resources from 0.1 to 1 l/s·km^2 have significantly less spreading (about 18% of the total area), they are characterized by low degree of vulnerability.

Table 5.9. The mean vulnerability index SINTACS, calculated for conditions of maximum infiltration, corresponding to different sites with various amount of natural groundwater resources (l/s·km^2)

Natural recourses of groundwater, (l/sec * km^2)	Area, км^2	Vulnerability index SINTACS				
		Min	Max	**Mean**	Degree of vulnerability	STD
5 - 10	24.6	25	91	54	high	12
2 - 5	**1003.5**	9	100	60	**high**	19
1 - 2	**1059.7**	0	100	48	**medium**	20
0.5 - 1	279.2	6	84	34	low	14
0.1 – 0.5	164.1	3	79	35	low	13

To estimate impact of each of the seven factors (parameters) SINTACS on the final vulnerability assessment there has been performed zonal statistics for each parameter (Fig. 5.4, 5.6, 5.13, 5.15, 5.16, 5.17, 5.19), ranked on the scale SINTACS (Table 5.1), in regards to the final vulnerability scheme (map) (Figure 5.22). The results of the statistical analysis are presented in Table. 5.10. The SINTACS factors and corresponding ratings within of each factor are presented in column «F» and in column «Rating». Area of sites with different ratings within of each of the factors (parameters) SINTACS is shown in the column «Area». In the next columns of Table 5.10 there are presented the static data of distribution of the final vulnerability index for sites with different ratings within of each of the factors. The prevailing vulnerability rating was determined by the mean value (column «Mean»).

Table 5.10. Impact of individual factors on the groundwater vulnerability degree according to SINTACS

F	Rating	Area, km^2	MIN	MAX	**MEAN**	VD	STD
S	1	122	6	64	32		10
	2	559	0	68	36		11
	3	563	4	77	41		11
	4	262	8	80	45		13
	5	282	12	84	53		16
	6	106	21	87	58		14
	7	81	25	90	62		14
	8	59	30	93	67		14
	9	49	33	97	72		14
	10	447	37	100	80		13
I	1	163	3	74	35		13
	2	278	6	84	34		14
	3	1060	0	88	48		20
	7	1005	16	100	60		19
	9	25	30	91	54		12
N	2	267	6	87	52		19
	3	103	0	84	37		13
	4	442	3	93	42		17
	5	984	5	97	42		13
	6	735	13	100	70		19
T	3	1329	0	97	51		25
	5	1140	10	100	51		14
	6	62	10	98	39		14
A	3	309	0	87	31		12
	4	437	9	89	45		14
	5	754	11	91	43		14
	6	419	17	98	52		14
	7	76	24	93	54		11
	8	537	29	100	77		16
C	4	484	0	87	39		16
	5	76	24	93	54		11
	6	1190	9	91	43		14
	7	773	17	100	69		20
	8	8	43	83	67		10
S	1	0.10	20	29	25		3
	2	0.16	23	39	34		4
	3	1	0	45	30		11
	4	3	2	74	33		13
	5	11	3	89	36		14
	6	62	5	93	37		14
	7	225	5	95	39		14
	8	330	3	97	42		15
	9	496	5	98	45		17
	10	1402	7	100	57		21

F factor of SINTACS
S depth to groundwater
I effective infiltration
N unsaturated zone
T soil capacity
A aquifer's characteristic
C hydraulic conductivity
S topographic slope

VD vulnerability degree

80 - 100
70 -79
50 - 69
36 - 49
25 -35
0 - 24

extremely high
very high
high
medium
low
very low

In accordance with the ten-point rating scale SINTACS within each of the factors the vulnerability increases from 1 to 10 (1 corresponds to the minimum vulnerability, 10 - the maximum.) As seen from the table, the first parameter «S» - depth to groundwater answers such distribution best of all others. Here, areas with rating "1" corresponds to low vulnerability, and sites with a rating of "9" and "10" - very high and extremely high vulnerability. In general, the parameters «A» (aquifer's characteristic), «I» (effective infiltration), «C» (hydraulic conductivity) correspond to such distribution. From this it can be concluded that the determining factors of groundwater vulnerability in the method SINTACS with regard to the studied area are the listed above factors: depth to groundwater, lithological composition and filtration characteristics of the aquifer, and effective infiltration. Attention is paid to the fact that for the parameters «N» (unsaturated zone) and «T» (soil capacity) there is observed the inverse distribution. So, on the map of parameter N, the sites with rating of "2" corresponds to high degree of vulnerability and areas with rating of "3", "4" and "5" - the medium degree of vulnerability. In other words, there is an inverse relationship. In our opinion, this is connected with the fact that for the parameter «N», which characterizes the lithological composition of the unsaturated zone, it is need to enter a coefficient that will take into account the thickness of the deposits in the unsaturated zone. In investigated territory the thickness of the unsaturated zone varies from 0 to 70 meters and more. Obviously, that various thickness of deposits of the unsaturated zone will impact on filtration of pollutants in different ways. Additional information concerning the relationship of individual parameters SINTACS among themselves and with the final map of vulnerability assessment can be obtained by performing their pairwise correlation. In Table. 5.11 there is represented the correlation matrix of the above-listed parameters calculated using the tool ArcGIS «Principal component analysis» (method of principal components). In the Table. 5.11, in the leftmost column and in the top row there are presented seven parameters (maps) SINTACS and final map of vulnerability, and in the remaining cells of the table there are given correlation coefficients between the parameters (maps). In the first row of the table are given correlation coefficients of the final vulnerability maps with individual parameters SINTACS. As can be seen from the table, the parameters «S» (depth to groundwater) and «A» (aquifer's characteristic) have a good correlation with final vulnerability map, correspondingly 0,78 and 0,67. The smaller values of correlation are observed for parameters "C» (hydraulic conductivity) - 0,45, «I» (effective infiltration) - 0,41 and the «S» (topographic slope) - 0,35. The smallest value of the correlation coefficient between the final map and map of the parameter «T» (soil capacity) says that this parameter («T») does not impact the final assessment of the vulnerability in the investigated territory (there is no correlation). The low value of the correlation between the «N» parameter's map (unsaturated zone) and the final map of vulnerability confirms the said above, namely, for the parameter «N» it should be entered a coefficient taking into account thickness of the deposits in the unsaturated zone. Table 5.12 shows the values of the correlation coefficient of parameters SINTACS, but here the parameters (factors) SINTACS are multiplied on the weights of these parameters in accordance with the values of the diagram (Figure 5.1). Selected hydrogeological and impact settings for SINTACS are shown in Fig. 5.20, and their multiplying factors (Strings of multiplier weights given for SINTACS) for the parameters can be seen in Fig. 5.21. From the Table 5.12 it is seen that for some parameters the correlation coefficient with the final vulnerability map has increased (A - aquifer's characteristic, C - hydraulic conductivity), and for other (N - unsaturated zone, S - topographic slope) - has become smaller. The low values of the correlation coefficient of parameters «N» and «S» with the final map of vulnerability indicate that the ranking of these parameters must be different from the original ranking (given in the methodology SINTACS) and take into account features of the territory.

With the soil map «T» there is a inverse correlation (-0.36). In other words, in the most part of the area with alluvial deposits, along with increase of vulnerability degree on the final map SINTACS, less vulnerability of the soil cover is observed. This is explained by the fact that the alluvial soils have heavy clay loam mechanical composition, and alluvial deposits of the unsaturated zone of large rivers on the contrary have good filtration characteristics.

Table 5.11. Correlation matrix of parameters SINTACS (Fig. 5.4, 5.6, 5.13, 5.15, 5.16, 5.17, 5.19) and the final map of the vulnerability assessment SINTACS (Fig. 5.22)

Layer	SINTACS vulnerability map	S	I	N	T	A	C	S
SINTACS vulnerability map	1	0.78	0.41	0.31	-0.04	0.67	0.45	0.35
S - depth to groundwater	0.78	1	0.03	0.05	-0.19	0.52	0.21	0.32
I - effective infiltration	0.41	0.03	1	0.03	0.01	-0.04	0.04	-0.09
N - unsaturated zone	0.31	0.05	0.03	1	-0.03	0.21	0.16	0.05
T - soil capacity	-0.04	-0.19	0.01	-0.03	1	-0.17	-0.07	-0.12
A - aquifer's characteristic	0.67	0.52	-0.04	0.21	-0.17	1	0.64	0.26
C - hydraulic conductivity	0.45	0.21	0.04	0.16	-0.07	0.64	1	0.07
S - topographic slope	0.35	0.32	-0.09	0.05	-0.12	0.26	0.07	1

Table 5.12. Correlation matrix of parameters SINTACS (Fig. 5.4, 5.6, 5.13, 5.15, 5.16, 5.17, 5.19) multiplying on the strings of weights (Figure 5.21) and the final map of the vulnerability assessment SINTACS (Fig. 5.22).

Layer	SINTACS vulnerability map	**S** x strings	**I** x strings	**N** x strings	**T** x strings	**A** x strings	**C** x strings	**S** x strings
SINTACS vulnerability map	1	0.74	0.33	0.16	-0.36	0.75	0.75	-0.11
S x strings	0.74	1	-0.01	-0.15	-0.35	0.56	0.53	-0.13
I x strings	0.33	-0.01	1	-0.06	0.21	-0.05	-0.09	-0.26
N x strings	0.16	-0.15	-0.06	1	-0.05	-0.01	0.05	0.20
T x strings	-0.36	-0.35	0.21	-0.05	1	-0.57	-0.65	-0.13
A x strings	0.75	0.56	-0.05	-0.01	-0.57	1	0.91	-0.30
C x strings	0.75	0.53	-0.09	0.05	-0.65	0.91	1	-0.11
S x strings	-0.11	-0.13	-0.26	0.20	-0.13	-0.30	-0.11	1

To compare the two maps of vulnerability assessment, constructed by two methods, there was estimated the average time of chloride ion travel to the groundwater level for maximum infiltration rate (Fig. 5.34) within the sites with different degrees of groundwater vulnerability by SINTACS method. This comparison was performed using a tool ArcGIS «Zonal Statistics». The results are presented in Table. 5.13 and Fig. 5.35. As seen in the table and the graph, in general, there is observed the relationship of mean values of travel time of chlorides with degree of groundwater vulnerability by SINTACS. The higher the degree of groundwater vulnerability by SINTACS, the less the average time of filtration of chlorides to the groundwater level. And vice versa, the minimum degree of vulnerability by SINTACS corresponds to the maximum time of travel of chlorides. At the same time there is a high value of standard deviation (STD in the table, «σ» - on the chart) that indicates that the value of time is greatly scattered about the mean. The correlation coefficient between two vulnerability maps (Fig. 5.22 and 5.34) calculated using the method of principal components makes up «-0,45» that corresponds to the moderate inverse relationship. Inverse relationship means that the greater vulnerability of groundwater by SINTACS, the less the time of travel of chlorides to the groundwater level and conversely.

Table 5.13. Average time (days) of travel of chloride ion to the groundwater level, for the maximum Infiltration rate, for areas with different degree of groundwater vulnerability assessed by method SINTACS

SINTACS vulnerability degree		Area, km^2	Mean, day	STD	"-" σ	"+" σ
1		203.9	1017	659	359	1676
2		397.1	902	738	163	1640
3		721.7	496	559	negative	1055
4		704.3	249	434	negative	684
5		153.6	172	376	negative	548
6		350.4	28	61	negative	89

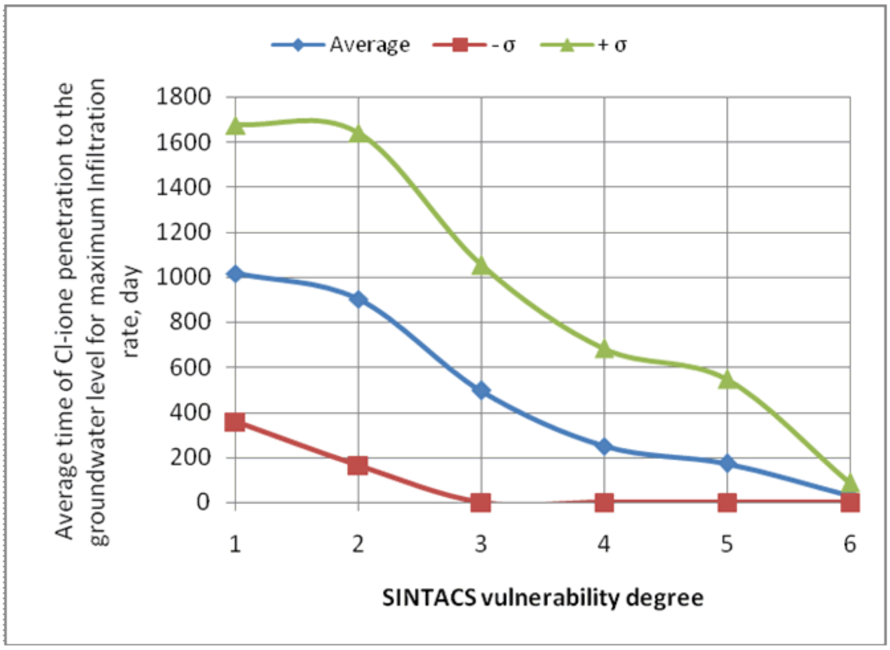


Figure 5.35. The graph of correspondence of vulnerability degree by SINTACS and the average time of travel of Cl ion to the groundwater level, for the maximum Infiltration rate.

To compare the time of travel of chlorides to the groundwater level of different aquifers there was used a tools "zonal statistics" of ArcGIS. The average values of chlorides travel time for conditions of the minimal infiltration rate are presented in Table 5.14, and for the maximum infiltration rate – in Table 5.15. It should be noted that the average values presented in the tables have a very relative nature, as is evident from the large scatter of the standard deviation of the mean. However, the performed statistical analysis allows us in whole to assess vulnerability of the individual aquifers. As can be seen from the tables, the time of travel of chlorides to the groundwater level for Sheshminsky water-bearing complex increases on the average in 3 times, and for Solikamsky terrigenous-carbonate complex - on the average in 3.5-4 times (in depends on the infiltration rate) in comparison with the alluvial aquifer.

Table 5.14. . The mean time of travel of Cl-ion to the groundwater level (days), calculated for conditions of the **minimum infiltration** for aquifers of the investigated territory

Index of the aquifer*	Area, км^2	Mean, day	STD
f Qel	70.4	1261	1963
aQ	689.5	313	937
P_1 ss	1022.9	897	1042
P_1 sl_2	789.7	1080	1275
P_1 sl_1	15.8	758	799

* See comment to Table 5.8

Table 5.15. The mean time of travel of Cl-ion to the groundwater level (days), calculated for conditions of the **maximum infiltration** for aquifers of the investigated territory

Index of the aquifer*	Area, км^2	Mean, day	STD
f Qel	70.4	591	718
aQ	689.5	159	411
P_1 ss	1022.9	465	443
P_1 sl_2	789.7	593	573
P_1 sl_1	15.8	439	293

* See comment to Table 5.8

Zonal analysis of the territory with different natural groundwater resources allows us to speak that the most vulnerable to pollution by neutral pollutants (chlorides) are the areas with greater groundwater resources (Table 5.16). Time of travel of chlorides is increased on the average in 1.7 times for the areas with the resources of 1-2 l/sec·km^2 and on the average in 4.5 times for the areas with the resources of 0.5 - 1 l/sec·km^2 in comparison with areas with greater natural groundwater resources (2-5 l/sec·km^2).

Table 5.16. The mean time of travel of Cl-ion to the groundwater level (days), calculated for conditions of the maximum infiltration, corresponding to different areas with various value of natural groundwater resources (l/s·km^2)

Natural recourses of groundwater, (l/sec * km^2)	Area, км^2	Mean, day	STD
5- 10	24.6	168	99
2 - 5	1010.3	234	306
1 - 2	1108.2	401	510
0.5 - 1	281.5	1039	907
0.1 - 0.5	163.6	1056	914

To assess the influence of the parameters taken into account when calculating the travel time of chlorides, using a tool "method of principal components", there was performed a correlation between the parameters and the final map of the travel time of chlorides for conditions with the maximum infiltration (Table 5.17) and the minimum infiltration (Table 5.18). The tables show that the main parameters that define the time of travel of chlorides through the unsaturated zone to the groundwater level are seepage velocity of infiltration flow, defined taking into account the infiltration rate, and hydraulic conductivity of deposits in the unsaturated zone. It should be noted that the correlations of different layers presented in Tables 5.17-5.18 was performed for non-classified rasters. In the case of their reclassification the correlation coefficient would be a little more significant.

Table 5.17. Correlation matrix of parameters taken into account when calculating the travel time of chlorides (Fig. 5.23, 5.24, 5.25, 5.26, 5.28, 5.30, 5.31, 5.32) and the resulting map (Fig. 5.34) **for the maximum infiltration rate**

Layer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	1	0.87	0.29	-0.39	-0.57	-0.31	0.17	-0.04	-0.44	0.05	-0.12	-0.04
2	0.87	1	0.01	-0.30	-0.46	-0.20	0.28	-0.11	-0.32	0.11	-0.10	-0.11
3	0.29	0.01	1	-0.19	-0.16	-0.34	-0.12	0.29	-0.21	-0.26	0.16	0.28
4	-0.39	-0.30	-0.19	1	0.54	0.66	-0.01	0.23	-0.02	-0.20	0.00	0.22
5	-0.57	-0.46	-0.16	0.54	1	0.30	-0.24	0.19	0.60	-0.19	0.29	0.19
6	-0.31	-0.20	-0.34	0.66	0.30	1	-0.01	-0.52	-0.04	0.51	-0.10	-0.52
7	0.17	0.28	-0.12	-0.01	-0.24	-0.01	1	0.01	-0.08	-0.03	0.29	0.02
8	-0.04	-0.11	0.29	0.23	0.19	-0.52	0.01	1	0.03	-0.93	0.09	1.00
9	-0.44	-0.32	-0.21	-0.02	0.60	-0.04	-0.08	0.03	1	-0.07	0.27	0.03
10	0.05	0.11	-0.26	-0.20	-0.19	0.51	-0.03	-0.93	-0.07	1	-0.10	-0.93
11	-0.12	-0.10	0.16	0.00	0.29	-0.10	0.29	0.09	0.27	-0.10	1	0.09
12	-0.04	-0.11	0.28	0.22	0.19	-0.52	0.02	1.00	0.03	-0.93	0.09	1

1 – map of total time of chloride ion penetration to the groundwater level
2 – map of time of chloride ion penetration through the strata of the Quaternary deposits
3 – map of time of chloride ion penetration through the strata of the Permian deposits
4 – map of **maximum** infiltration rate
5 – seepage velocity of infiltration flow of the Quaternary deposits
6 – seepage velocity of infiltration flow of the Permian deposits
7 – saturated water content (Θs) of the Quaternary deposits
8 – saturated water content (Θs) of the Permian deposits
9 – hydraulic conductivity of the Quaternary deposits (unsaturated zone)
10 – hydraulic conductivity of the Permian deposits (unsaturated zone)
11 – effective (active) porosity of the Quaternary deposits
12 – effective (active) porosity of the Permian deposits

Table 5.18. Correlation matrix of parameters taken into account when calculating the travel time of chlorides (Fig. 5.23, 5.24, 5.25, 5.26, 5.27, 5.29, 5.31, 5.32) and the resulting map (Fig. 5.33) **for the minimum infiltration rate**

Layer	1	2	3	4	5	6	7	8	9	10	11	12
1	1	0.89	0.29	-0.40	-0.53	-0.33	0.19	-0.05	-0.37	0.06	-0.08	-0.05
2	0.89	1	0.05	-0.32	-0.44	-0.23	0.24	-0.10	-0.28	0.11	-0.08	-0.10
3	0.29	0.05	1	-0.21	-0.18	-0.35	-0.11	0.25	-0.19	-0.23	0.16	0.25
4	-0.40	-0.32	-0.21	1	0.51	0.63	-0.01	0.21	-0.01	-0.19	-0.01	0.21
5	-0.53	-0.44	-0.18	0.51	1	0.27	-0.25	0.18	0.62	-0.19	0.29	0.18
6	-0.33	-0.23	-0.35	0.63	0.27	1	-0.01	-0.55	-0.04	0.54	-0.10	-0.55
7	0.19	0.24	-0.11	-0.01	-0.25	-0.01	1	0.01	-0.08	-0.03	0.29	0.02
8	-0.05	-0.10	0.25	0.21	0.18	-0.55	0.01	1	0.03	-0.93	0.09	1.00
9	-0.37	-0.28	-0.19	-0.01	0.62	-0.04	-0.08	0.03	1	-0.07	0.27	0.03
10	0.06	0.11	-0.23	-0.19	-0.19	0.54	-0.03	-0.93	-0.07	1	-0.10	-0.93
11	-0.08	-0.08	0.16	-0.01	0.29	-0.10	0.29	0.09	0.27	-0.10	1	0.09
12	-0.05	-0.10	0.25	0.21	0.18	-0.55	0.02	1.00	0.03	-0.93	0.09	1

1 – map of total time of chloride ion penetration to the groundwater level
2 – map of time of chloride ion penetration through the strata of the Quaternary deposits
3 – map of time of chloride ion penetration through the strata of the Permian deposits
4 – map of the **minimum** infiltration rate
5 – seepage velocity of infiltration flow of the Quaternary deposits
6 – seepage velocity of infiltration flow of the Permian deposits
7 – saturated water content (Θs) of the Quaternary deposits
8 – saturated water content (Θs) of the Permian deposits
9 – hydraulic conductivity of the Quaternary deposits (unsaturated zone)
10 – hydraulic conductivity of the Permian deposits (unsaturated zone)
11 – effective (active) porosity of the Quaternary deposits
12 – effective (active) porosity of the Permian deposits

In Fig. 5.36 there is presented a map that shows that in the studied area, when the infiltration rate changing from the minimum to the maximum value, the time of travel of neutral pollutants (chlorides) through the unsaturated zone to the groundwater level is reduced in 1.6-2.9 times (on the average in 2 times).

The high value of correlation coefficient "0.89" of map of the total travel time of chlorides and maps of travel time through the upper Quaternary layer only (Table 5.17-5.18) underlines the basic role of the Quaternary deposits in the unsaturated zone. For the 65% of the total territory under research approximately from 80 to 100% of the total time of travel of chlorides through the unsaturated zone is connected only with the Quaternary deposits (Figure 5.37).

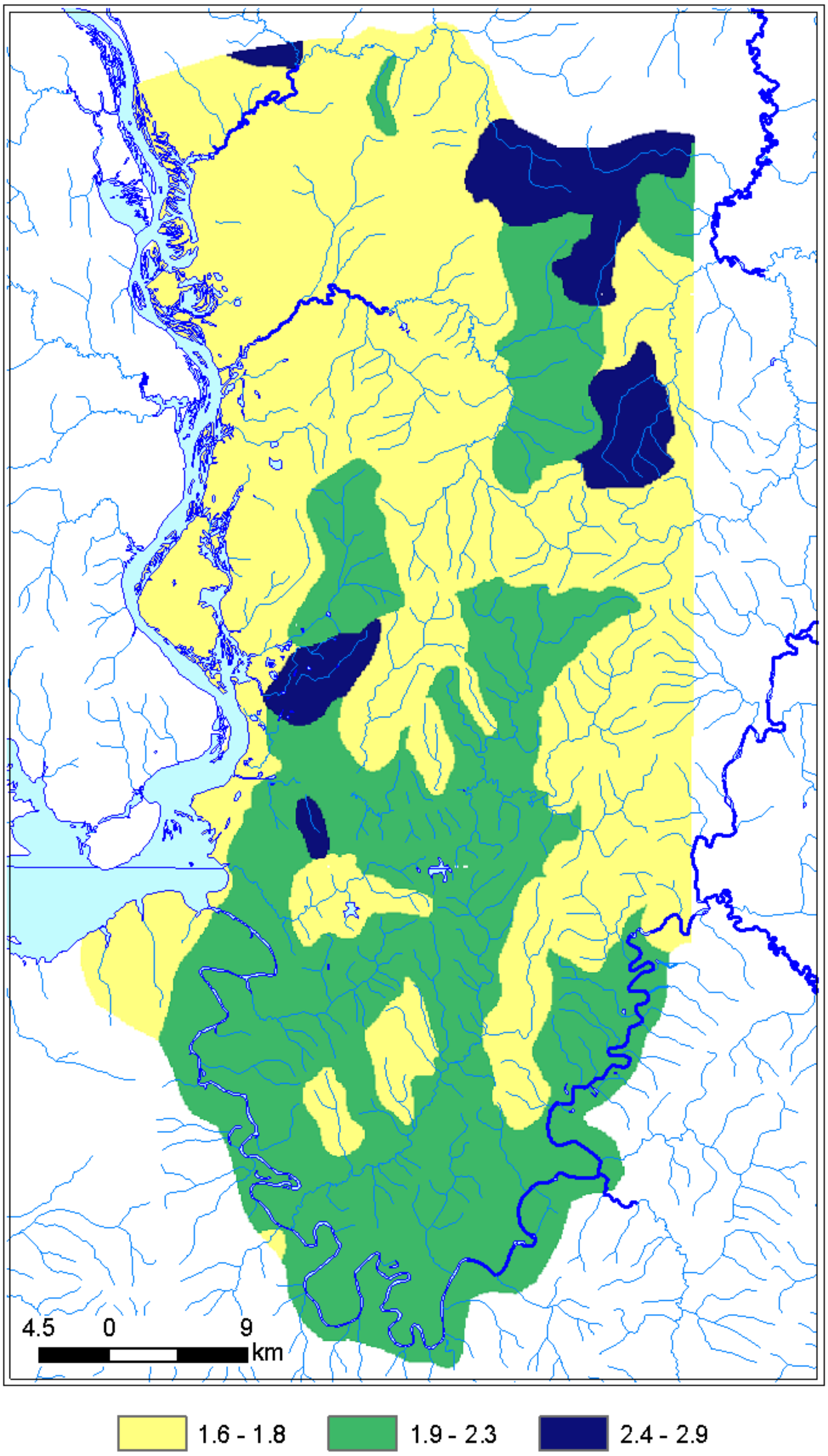
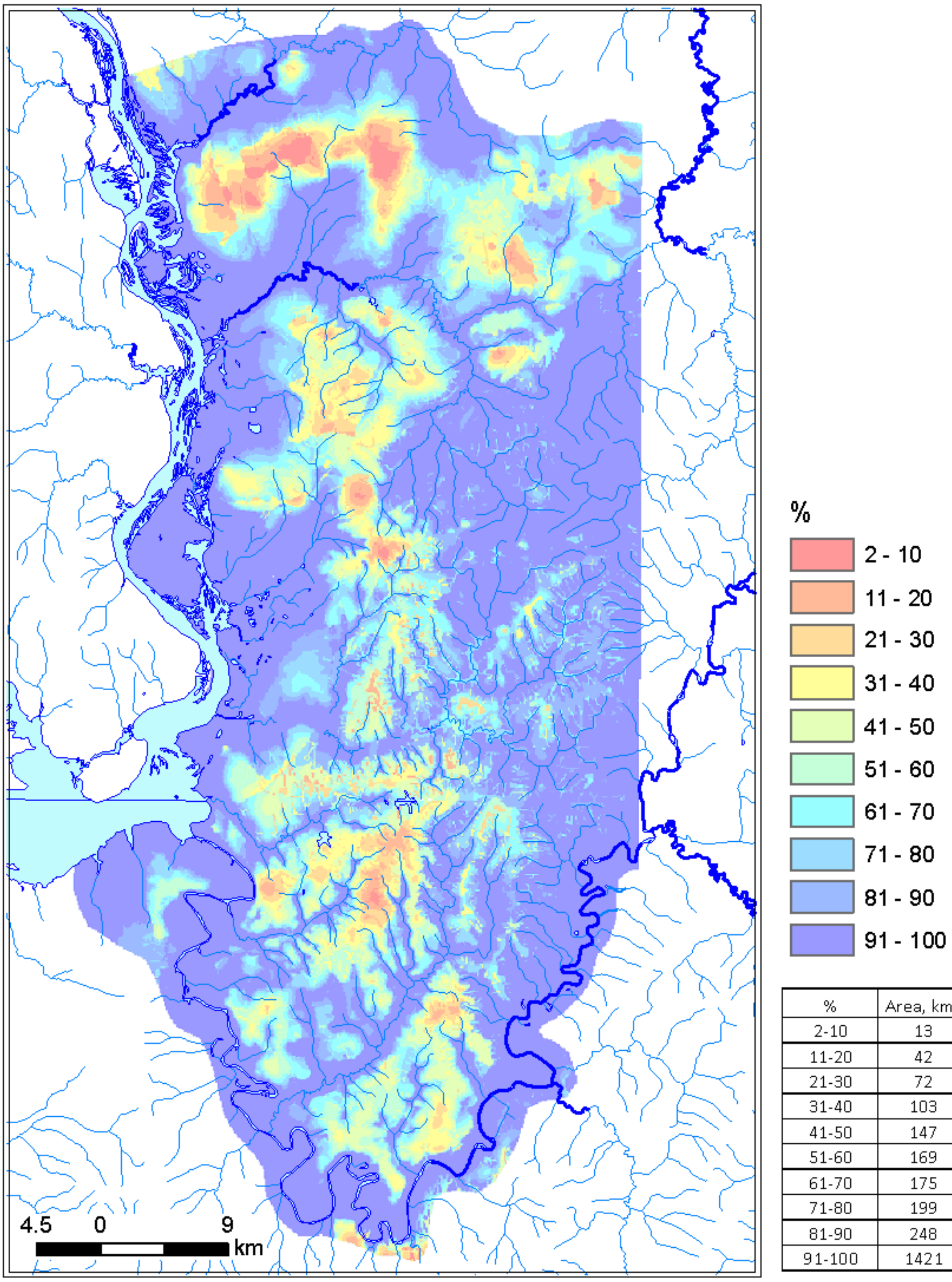


Figure 5.36. The coefficient of increasing of the travel time of chloride ion to the groundwater level at the increasing of infiltration from the minimum to the maximum value



%	Area, km^2
2-10	13
11-20	42
21-30	72
31-40	103
41-50	147
51-60	169
61-70	175
71-80	199
81-90	248
91-100	1421

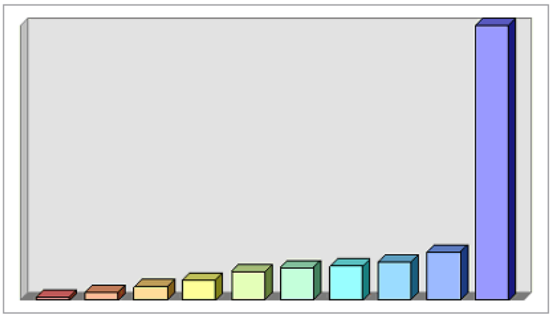


Figure 5.37. Time of travel of chlorides through the upper layer of the unsaturated zone (the Quaternary deposits) in% of the total time

Conclusion

The value of natural resources of groundwater, expressed by the module of groundwater runoff, on 80% of the studied area is on average of 1.5 – 3.5 l / sec $\cdot$km^2. On approximately half (43%) of the territory the value of module of groundwater runoff changes from 1 to 2 l/s$\cdot$km^2, on another smaller (39%) part – from 2 to 5 l/sec$\cdot$km^2. On the rest part of the territory (about 17% of the area) value of groundwater runoff is less than 1 l/sec$\cdot$km^2.

Natural groundwater resources of Sheshminsky water-bearing complex make up on average 2-5 l/s$\cdot$km^2, resources of Solikamsky terrigenous-carbonate complex and alluvial horizons – 1 to 2 l/sec $\cdot$km^2. In the valley of r. Yayva the resources of alluvial horizon are increased to 2-5 l/sec$\cdot$km^2.

Assessment of groundwater vulnerability to pollution made by two different methods for the same investigated territory showed that the alluvial aquifer is characterized by the greatest vulnerability (on the average "very high" degree of vulnerability by SINTACS) and also by the minimum, on the average, time of travel of chlorides from the land surface to the aquifer (the time was calculated for the conditions of the convective transport without taking into account diffusion and hydraulic dispersion (piston displacement)). Sheshminsky water-bearing complex and Solikamsky terrigenous-carbonate complex are mostly characterized by «medium» vulnerability by SINTACS. The time of travel of chlorides to the groundwater level for Sheshminsky water-bearing complex increases on the average in 3 times, and for Solikamsky terrigenous-carbonate complex - on the average in 3.5-4 times (in depends on the infiltration rate) in comparison with the alluvial aquifer.

The sites of the studied area where the value of natural groundwater resources varies from 2 to 5 l/sec$\cdot$km^2 have the greatest vulnerability to pollution (on the average the «high» degree of vulnerability by SINTACS), the areas with natural resources from 1 to 2 l/sec$\cdot$km^2 on average are characterized by «medium» degree of vulnerability by SINTACS. In accordance with the executed calculations of time of travel of chlorides the more vulnerable areas to pollution are the areas with greater groundwater resources. Time of travel of chlorides is increased on the average in 1.7 times for the areas with the resources of 1-2 l/sec$\cdot$km^2 and on the average in 4.5 times for the areas with the resources of 0.5 - 1 l/sec$\cdot$km^2 in comparison with areas with greater natural groundwater resources (2-5 l/sec$\cdot$km^2).

Major parameters that determine the vulnerability of groundwater by method SINTACS for the territory of the Upper Kama potassium salt deposit are the depth to groundwater, lithological composition and filtration characteristics of the aquifer, and in a less degree - the value of infiltration rate. At the same time, there is no connection between such important parameter of vulnerability as the lithological composition of the unsaturated zone (parameter «N») and the final map of groundwater vulnerability performed by the method SINTACS. The unsaturated zone in the study area varies from 0 to 65 m and more. In these conditions, there is proposed when determining the parameter «N» to enter the correction factor that takes into account the thickness of deposits of the unsaturated zone.

The main parameters that define the time of travel of chlorides through the unsaturated zone to the groundwater level are seepage velocity of infiltration flow, defined taking into account the infiltration rate, and hydraulic conductivity of deposits in the unsaturated zone.

In the studied area, when the infiltration rate changing from the minimum to the maximum value, the time of travel of neutral pollutants (chlorides) through the unsaturated zone to the groundwater level is reduced in 1.6-2.9 times (on the average in 2 times).

Analysis of the geological columns of more than 400 wells allowed to estimate the thickness of the upper layer of the unsaturated zone, represented by Quaternary deposits, and the thickness of the lower layer, represented by terrigenous-carbonate deposits of the Permian system. Approximately 40% of the territory has a single-layered unsaturated zone composed by Quaternary deposits only. For the 65% of the total territory under research approximately from 80 to 100% of the total time of travel of chlorides through the unsaturated zone is connected only with the Quaternary deposits.

The correlation coefficient between two maps of vulnerability (SINTACS and time of travel maps) calculated using the method of principal components makes up «-0,45». Inverse correlation means that the greater vulnerability of groundwater by SINTACS, the less the time of travel of chlorides to the groundwater level and conversely. The moderate value of the correlation coefficient is explained by fundamental differences in the vulnerability assessment for the two methods. And also the fact that for the greater part of the researched territory with different geological structure, hydrogeological and hydrological conditions when evaluating by the method SINTACS one of the leading parameters were the characteristics of the aquifer, and for the method based on the time calculation - the infiltration rate and parameters of rocks in the aeration zone. In general, there is observed a general tendency in the assessment of groundwater vulnerability for these two methods: the higher the degree of groundwater vulnerability by SINTACS, the less, on the average, the time of travel of the pollutant from the surface to the groundwater level.

In the future there is recommended to continue the research in this direction, with a focus on the experimental researches for clarifying the migration parameters of chlorides on waste disposal sites of salt industry.

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Appendix 1. Hydrographic characteristics

Name of rivers	Where is a river flows into and from which riverside	Distance from a mouth , km	Length of a river, km	Catchment area, km^2	Tributaries length less than 10 km		Lakes in the catchment area	
					Number	Total length, km	number	total water surface area, km^2
Borovaya (Borovica)	Kama reservoir (left)	930	53	543	42	85	3	0,05
Malaya Potymka	Borovaya (left)	35	12		4	9,9		
Potymka	Borovaya (left)	32	16		4	7,9		
Azlas	Borovaya (right)	20	13		6	14		
Korel	Borovaya (right)	16	17		11	23		
Usolka	Kama reservoir (left)	919	57	506	46	107		
Bolshoj Eg	Usolka (right)	42	10		13	20		
Rostovica	Usolka (right)	31	16		8	20		
Selyanka	Usolka (left)	15	14		9	22		
Tolych	Kama reservoir (left)	891	12	35,1	6	7,2		
Zyrianka (Izver)	Kama reservoir (left)	889	53	365	55	77	1	0,02
Talitsa	Zyrianka (left)	32	13		23	34	1	0,02
Legchim	Zyrianka (right)	24	28		51	60		
Bygel'	Zyrianka (right)	6,6	15		4	5,3		
Lenva	Kama reservoir (left)	881	21		25	28		
Yayva	Kama reservoir (left)	879	304	6250	267	506	12	3,52
Zhukla	Jayva (right)	80	12		13	13		
Unva (Bolshaja Unva)	Jayva (right)	40	41		45	84		
Malaja Unva (Ustinkova Unva)	Unva(left)	21	14		19	21		
Vogulka	Jayva (left)	39	13		21	32		
Volim	Jayva (right)	7,8	12		31	38		

Appendix 2. Calculation of the transition coefficient (Kt) and minimum runoff modules of 90% probability for small rivers (Baldin et al, 1998)

Q90% r. Yayva summer - 8,35 м^3/sec; Q90% r. Yayva winter - 7,08 м^3/sec

Number of a river station (section line)	River	Date of measuring	Measured discharge m^3 /sec	River – analogue: r. Yayva (village Baza)		Discharge in a section line of 90% probability	Catchment basin, km^2	Module of summer runoff of 90% of probability, l/s *km^2	Module of winter runoff of 90% of probability, l/s * km^2
				discharge m^3/sec	Kt				
5001	Talitsa	21.07.90	0,135	37,0	0,0036	0,03	39,06	0,76	0,64
5002	Malaya Talitsa	21.07.90	0,207	37,0	0,0056	0,047	8,18	5,7	4,8
5003	Izver	21.07.90	0,618	37,0	0,017	0,14	57,37	2,44	2,07
5004	Izver	21.07.90	3,28	37,0	0,089	0,74	233,9	3,16	2,68
5005	Bygel	21.07.90	0,374	37,0	0,01	0,084	38,16	2,2	1,86
5006	Stream Bezimyanny (Usolie)	22.07.90	0,037	34,5	0,0011	0,009	19,44	0,46	0,39
5007	r. Volim	22.07.90	0,78	34,5	0,023	0,19	57,86	3,28	2,78
5008	Stream bezimyanny (r. Volim)	22.07.90	0,06	34,5	0,0017	0,014	2,1	6,7	5,7
5009	Lenva II (Balahontsy)	22.07.90	0,545	34,5	0,016	0,13	45,05	2,89	2,45
5010	Lenva I (Zyachya gorka)	22.07.90	0,611	34,5	0,018	0,15	54,78	2,74	2,32
5011	Rostovitsa	9.08.90	0,262	17,6	0,015	0,12	17,82	6,7	5,68
5012	Rostovitsa	9.08.90	0,621	17,6	0,035	0,29	60,86	4,76	4,03
5013	Permyanka	9.08.90	0,069	17,6	0,004	0,033	9,91	3,33	2,82
5014	Bubrovka	9.08.90	0,193	17,6	0,011	0,092	17,82	5,16	4,37
5015	Berezovka	9.08.90	0,106	17,6	0,006	0,05	9,56	5,23	4,43
5016	Bolshoi Eg	12.08.90	0,121	16,8	0,0072	0,06	34,76	1,73	1,47
5017	Selyanka	12.08.90	0,117	16,8	0,007	0,058	60,21	0,96	0,81
5018	Berezovka	30.08.90	0,041	16,4	0,0025	0,021	5,59	3,76	3,19
5019	stream Korel	30.08.90	0,47	16,4	0,029	0,242	16,04	15,1	12,8
5020	Korel	30.08.90	0,355	16,4	0,022	0,184	35,57	5,17	4,38
5021	Izver	2.09.90	0,196	17,4	0,011	0,092	45,145	2,04	1,73
5022	Korel	9.09.90	0,7	12,8	0,055	0,46	91,25	5,04	4,27
5023	Azlas	9.09.90	0,411	12,8	0,032	0,267	44,32	6,02	5,1
5024	Serduk	9.09.90	0,163	12,8	0,013	0,108	38,45	2,81	2,38
5025	Cheremshanka	3.07.91	0,022	23,0	0,001	0,008	4,004	2,0	1,69
5026	Sylva	3.07.91	0,171	23,0	0,007	0,058	9,01	6,4	5,42
5027	Sylva	3.07.91	0,22	23,0	0,01	0,084	11,51	7,3	6,19

5029	Pashkovka	19.06.91	0,002	48,8	0,00004	0,0003	9,01	0,03	0,03
5030	Usolka	19.06.91	0,60	48,8	0,012	0,1	57,36	1,74	1,47
5031	Right tributary of Pesyanka	5.07.91	0,035	22,9	0,0015	0,012	6,006	2,0	1,69
5032	Pesyanka	5.07.91	0,196	22,9	0,0086	0,072	22,12	3,25	2,75
5033	Right tributary of Unva	6.07.91	0,08	22,6	0,0035	0,029	10,454	2,77	2,35
5034	Malaya Palasherka	6.07.91	0,083	22,6	0,0037	0,031	12,642	2,45	2,08
5035	Bolshaya Palasherka	6.07.91	0,203	22,6	0,009	0,075	13,51	5,55	4,7
5036	Unva	6.07.91	2,77	22,6	0,122	1,03	159,16	6,47	5,48
5037	Stream Bezimyanny (tributary of Yaiva)	20.06.91	0,08	58,6	0,0014	0,012	12,7	0,94	0,8
5038	Unva	11.07.91	0,42	22,1	0,019	0,159	76,88	2,07	1,75
5039	Bolshaya Unva	11.07.91	0,42	22,1	0,019	0,159	39,74	4,0	3,39
5040	Bolshaya Pesiaika	11.07.91	0,041	22,1	0,0019	0,016	6,406	2,5	2,12
5041	Malaya Pesiaika	11.07.91	0,031	22,1	0,0014	0,012	4,052	2,96	2,51
5042	Chizhanka	13.07.91	0,12	21,4	0,0056	0,047	14,314	3,28	2,78
5043	Chizhanka	13.07.91	0,06	21,4	0,0028	0,023	7,4	3,11	2,64
5044	Bolshaya Palasherka	13.07.91	0,053	21,4	0,0025	0,021	10,78	1,95	1,65
5045	Olkhovka	3.07.91	0,021	23,0	0,0009	0,008	5,3	1,51	1,28
5046	Legchim	3.07.91	0,78	23,0	0,034	0,28	64,46	4,34	3,68
5047	Orlovka	3.07.91	0,048	23,0	0,0021	0,018	4,404	4,09	3,47
5048	Bubrovka	8.08.90	0,137	18,3	0,0075	0,063	5,005	12,58	10,7
5051	Shelepaevka	13.07.91	0,132	21,4	0,006	0,05	6,306	7,93	6,72
5052	Lenva II	13.07.91	0,158	21,4	0,0074	0,062	14,41	4,3	3,6
5053	Kryjaevka	4.08.91	0,026	135	0,0002	0,002	3,804	0,52	0,44
5060	Chernaya	16.08.92	0,091	54,8	0,0017	0,014	12,5	1,1	0,93
5061	Volim	16.08.92	0,219	54,8	0,004	0,033	25,53	1,3	1,1
5062	Chernaya	17.08.92	0,007	51,8	0,0001	0,001	2,4	0,42	0,36
5063	Borovaya	19.08.92	4,171	55,7	0,075	0,63	467,66	1,35	1,14
5064	Unnamed tributary (r. Borovaya)	20.08.92	0,153	51,4	0,003	0,025	7,08	3,53	3,0
5065	Azlas	20.08.92	0,419	51,4	0,0082	0,068	56,06	1,21	1,02
5066	Unnamed tributary (r. Borovaya)	20.08.92	0,006	51,4	0,0001	0,0008	4,79	0,2	0,17
456	Utbischnaya	16.06.91	0,09	42,4	0,002	0,017	1,3	13,1	11,1
418	Right tributary (r. Krestovik)	18.08.90	0,021	16,4	0,0013	0,011	5,906	1,9	1,61
233	Right tributary (r. Bygel)	14.08.90	0,018	16,1	0,001	0,008	1,101	7,27	6,16
227	Mokroguska	11.08.90	0,021	16,8	0,001	0,0084	3,003	2,8	2,37

213	Right tributary (r. Berezovka)	8.08.90	0,045	18,3	0,0041	0,034	1,902	17,9	15,2
212	Berezovka (r. Usolka)	8.08.90	0,088	18,3	0,0048	0,04	4,605	8,7	7,4
204	Unnamed tributary (r. Kama)	23.07.90	0,013	32,5	0,0004	0,0033	1,902	1,74	1,47
203	Unnamed tributary (r. Kama)	23.07.90	0,036	32,5	0,001	0,0084	5,606	1,5	1,27
201	Unnamed tributary (r. Kama)	23.07.90	0,01	32,5	0,0003	0,0025	4,705	0,53	4,5
15	Meshalka	5.08.90	0,023	19,5	0,0012	0,01	5,105	1,96	1,66
14	Plehovsky log	5.08.90	0,078	19,5	0,004	0,033	4,104	8,04	6,81

Index of the deposits	ρ_s	**n**	**e**	**Θs**	**Description of the deposits**
alluvial	2.73	0.43	0.76	0.28	stiff loam
alluvial	2.73	0.44	0.77	0.28	stiff loam
alluvial	2.72	0.26	0.35	0.13	gravel with sand
alluvial	2.79	0.50	0.99	0.35	stiff loam
alluvial	2.72	0.47	0.89	0.33	clay semisolid
alluvial	2.70	0.38	0.62	0.23	loam semisolid
alluvial	2.73	0.44	0.79	0.29	solid clay
alluvial	2.78	0.46	0.86	0.31	loam semisolid
alluvial	2.71	0.32	0.47	0.17	solid loam
dealluvial	2.71	0.40	0.67	0.25	clay semisolid
dealluvial	2.74	0.44	0.78	0.28	loam semisolid
dealluvial	2.72	0.39	0.65	0.24	pebble ground with loamy filler
dealluvial	2.72	0.45	0.82	0.30	gravelly loam
dealluvial	2.72	0.46	0.85	0.31	solid loam
dealluvial	2.71	0.40	0.67	0.25	pliant loam
eluvial-dealluvial	2.74	0.51	1.05	0.38	pliant klay
eluvial-dealluvial	2.75	0.41	0.68	0.25	solid loam
eluvial-dealluvial	2.73	0.40	0.66	0.24	loam with c rabble
P_2 ss	2.70	0.19	0.23	0.09	limestone
P_2 ss	2.70	0.24	0.32	0.12	limestone
P_2 ss	2.70	0.16	0.19	0.07	limestone
P_2 ss	2.69	0.22	0.28	0.10	limestone
P_2 ss	2.69	0.28	0.39	0.14	limestone
P_2 ss	2.67	0.14	0.16	0.06	limestone
P_2 ss	2.71	0.20	0.25	0.09	limestone
P_2 ss	2.70	0.19	0.23	0.09	limestone
P_2 ss	2.72	0.22	0.28	0.10	limestone
P_2 ss	2.71	0.27	0.37	0.14	limestone
P_2 ss	2.71	0.32	0.47	0.17	limestone
P_2 ss	2.74	0.35	0.54	0.20	limestone
P_2 ss	2.72	0.36	0.56	0.21	siltstone
P_2 ss	2.74	0.50	1.00	0.36	siltstone
P_2 ss	2.72	0.38	0.61	0.23	siltstone
P_2 ss	2.70	0.27	0.37	0.14	siltstone
P_2 ss	2.73	0.33	0.49	0.18	siltstone
P_2 ss	2.70	0.41	0.69	0.26	siltstone
P_2 ss	2.74	0.29	0.41	0.15	siltstone
P_2 ss	2.76	0.36	0.56	0.20	siltstone
P_2 ss	2.81	0.31	0.45	0.16	siltstone
P_2 ss	2.78	0.33	0.49	0.18	siltstone
$P_2\ sl_2$	2.73	0.34	0.52	0.19	limestone
$P_2\ sl_2$	2.71	0.14	0.16	0.06	limestone
$P_2\ sl_2$	2.68	0.18	0.22	0.08	limestone
$P_2\ sl_2$	2.75	0.31	0.45	0.16	limestone

$P_2\ sl_2$	2.70	0.15	0.18	0.07	marl
$P_2\ sl_2$	2.71	0.26	0.35	0.13	marl
$P_2\ sl_2$	2.69	0.21	0.27	0.10	siltstone
$P_2\ sl_2$	2.71	0.18	0.22	0.08	siltstone
$P_2\ sl_2$	2.76	0.28	0.39	0.14	siltstone
$P_2\ sl_2$	2.67	0.12	0.14	0.05	siltstone
$P_2\ sl_2$	2.72	0.19	0.23	0.09	siltstone
$P_2\ sl_2$	2.75	0.25	0.33	0.12	siltstone
	2.67	38.10	0.62	0.23	fine sand
	2.66	38.30	0.62	0.23	fine sand
	2.67	27.70	0.38	0.14	light sandy loam
	2.68	47.60	0.91	0.34	debris ground
	2.71	42.20	0.73	0.27	rubbly ground
	2.64	47.40	0.90	0.34	fine sand
	2.65	35.50	0.55	0.21	medium sand
	1.69	80.10	4.03	2.38	peat
	1.60	90.90	9.94	6.21	peat
	2.71	46.00	0.85	0.31	argillite medium solidity
	2.68	36.80	0.60	0.22	pliant sandy loam
	2.73	40.00	0.65	0.24	loam with debris
	2.74	30.00	0.40	0.15	rubbly ground

ρ_s – soils and rock-particle density (g/cm^3)

n – porosity of the rocks, fraction of unity

e – coefficient of reduced porosity, fraction of unity

θ_s – saturated water content, fraction of unity